2. Atmospheric Processes

The Lake Tahoe Basin lies between crests of the Sierra Nevada and Carson mountain ranges. The surface of Lake Tahoe is 1,900 meters (6230 feet) above mean sea level and has an irregular oval shape, 35 kilometers (22 miles) long by 19 kilometers (12 miles) wide, comprising an area of 500 square kilometers (193 square miles). Lake Tahoe is a deep lake (as deep as 505 meters or 1645 feet) and contains a large volume of water – factors which keep the water temperature relatively stable throughout the year. The Lake itself dominates the watershed (almost 40% of the surface area). The alpine features encircling the Lake create a bowl appearance. These topographic features have a significant influence on the meteorology of the Basin.

The meteorological characteristics of the Tahoe Basin are largely determined by its geographic setting. On the large or synoptic scale, its location near the eastern edge of the semi-permanent eastern Pacific high pressure system influences the seasonal patterns of temperature and precipitation. On the regional scale, its alpine topography strongly influences the spatial patterns of winds, temperature, and precipitation. On the local scale, the different interactions of the air with the ground and Lake result in the formation of complex temperature inversion layers and local winds which create perceptible differences in meteorological conditions over short distances. All of these different meteorological scales contribute to the unique meteorology of the Tahoe Basin.

Not only do meteorological processes determine the weather at a particular location, they also help to determine the air quality. Emission sources and activities add materials to the air. Depending on the nature of the material (e.g., gas, aerosol, reactive, “sticky”, size), these materials can move long distances with the wind or can “disappear” rapidly; they can be very concentrated at one location and non-detectable a short distance away. Because the meteorology strongly influences the emission, transformation, dissipation, and deposition of materials, ARB staff has made meteorological measurements a major component of the Lake Tahoe Atmospheric Deposition Study. Without detailed knowledge of the temporal and spatial (horizontal and vertical) variations in temperature and wind, the characterization of the relative impacts of various global, regional, and local sources of nutrients and aerosols contributing to the declining water clarity in Lake Tahoe would be compromised.

2.1 Precipitation Patterns

Precipitation is a factor in the annual deposition of materials to the Tahoe Basin. Precipitation is generally associated with good air quality due to enhanced dispersion and deposition of pollutant emissions. However, anthropogenic emissions of very small particles can also serve as condensation nuclei and deposit to the Lake. More importantly, the falling precipitation can “wash” the lower atmosphere of pollutants and stabilize soils, reducing windblown dust. In general, the first period of precipitation during a storm contributes the bulk of the total wet deposition of pollutants from the storm. When the precipitation falls as snow, an additional source of nutrients and aerosols is created by the application of road sanding materials. The air quality and depositional impacts of road sanding will vary, depending on the composition and size of the sanding material as well as the efficiency of road sweeping operations.

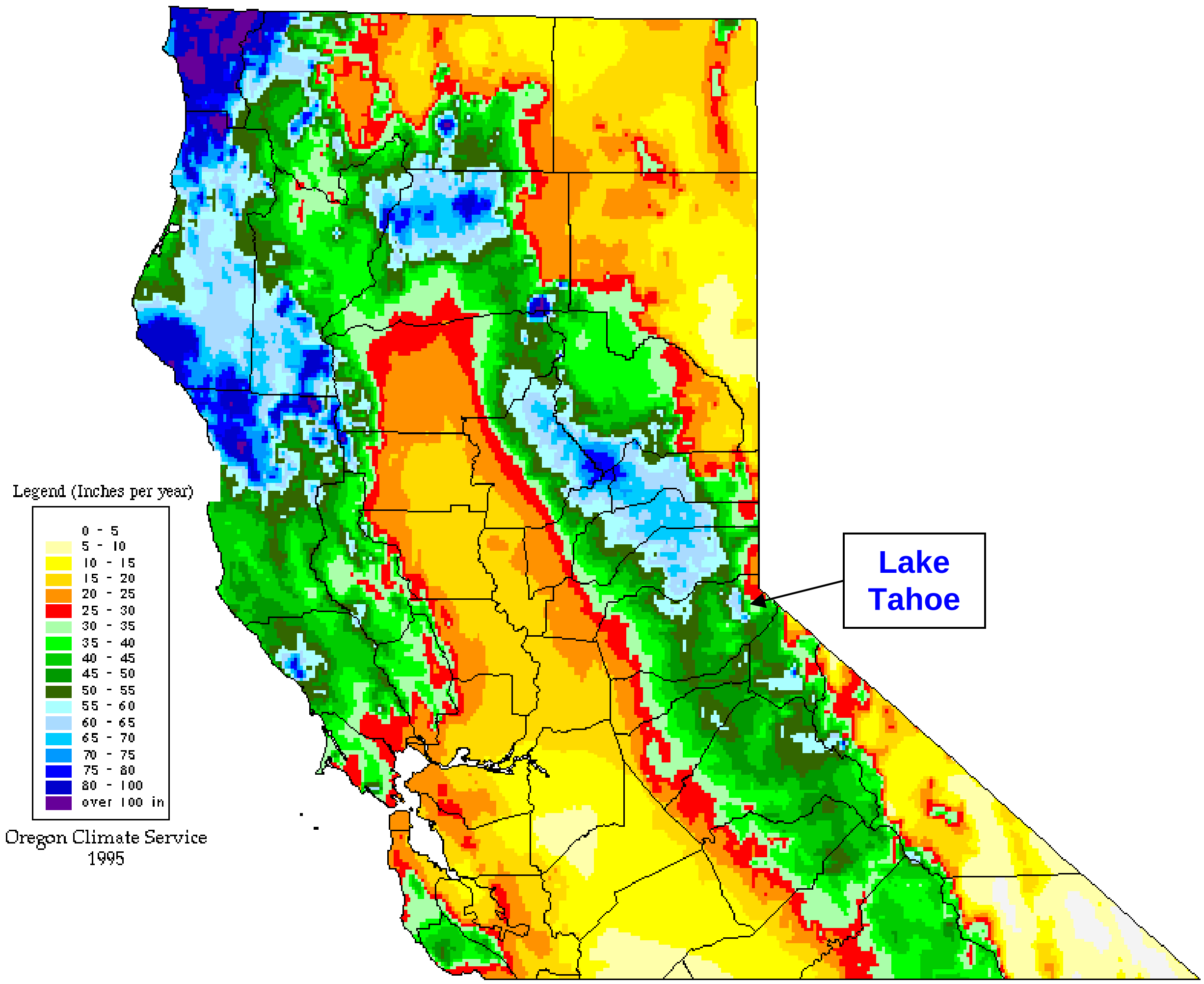
Tahoe's proximity to the Pacific Ocean provides it with a source of moisture for precipitation. The eastern Pacific high pressure system creates a Mediterranean type of climate with most of the precipitation occurring during relatively mild winters (November through March). At an elevation greater than 6,000 feet, much of the precipitation in the Basin occurs as snow. When synoptic scale weather systems are not present, the regional topography (alpine basin) influences the diurnal wind and temperature patterns via up-slope and down-slope breezes. The orographic lift provided by the Sierra Nevada to the air arriving from the west causes much of the precipitation to occur just west of the basin (**Figure 2-1**). Although the amount of precipitation during the winter varies from year to year, on average, over 60 inches (") of precipitation falls along the Sierra crest, about 30" along the western shore of the Lake, 20-30" over the Lake itself (less on the eastern side), and increasing to about 30" near the top of the Carson Range on the eastern side of the Tahoe Basin.

A map identifying the locations of many meteorological monitoring sites discussed in this report is provided in **Figure 2-2**. As illustrated in **Figure 2-3**, precipitation amounts on the eastern side of the Lake are similar to that on the western side during the summer when showers provide most of the meager precipitation. During winter months when synoptic storms dominate precipitation patterns, precipitation is approximately double on the western side of the Lake as that on the eastern side.

As illustrated in **Figure 2-4**, the frequency of precipitation is more similar throughout the region than are precipitation amounts. The normal number of days with measurable precipitation in the Tahoe Basin is indicated by the dashed line in **Figure 2-4** and is the mean of the three sites in the Basin (i.e., Tahoe City, Stateline, and Glenbrook). In fact, the frequency of precipitation in 2003 exhibited more spatial uniformity than normal during the winter and spring (**Figure 2-5**). Because of the relative infrequency and scatter nature of thundershowers during the summer, it is not unusual that Incline Village experienced twice the summer norm while Meyers experienced slightly fewer than normal.

Precipitation data for Incline Village were readily available during LTADS and were used to estimate wet deposition to Lake Tahoe. Hourly and daily precipitation totals at Incline Village during 2003 are shown in **Figures 2-6 and 2-7**. **Figure 2-6**, which presents hourly precipitation totals at Incline Creek during 2003, indicates like the other sites with long-term precipitation records in the Basin that the most intense precipitation is associated with summer thunderstorms. The 2003 precipitation data for Incline Village also indicate that most of the annual precipitation was associated with organized storm systems in the winter and early spring (**Figure 2-7**). This pattern is consistent with the seasonal norms (**Figure 2-8**), although 2003 exhibited some deviations from normal. Although storms were relatively frequent in January and February of 2003 (equal to long-term norm), they were not as strong as normal and so did not deliver as much

Figure 2-1. Annual Precipitation (inches) in Northern California-1691-90 Mean. (Source: www.wrcc.dri.edu/pcpn/ca_north.gif. Note the enhanced precipitation along the western slope of the Sierra Nevada due to orographic lifting of the air. Storm systems typically move from the west southwest toward the east northeast. The Tahoe Basin is on the lee side of the Sierra where annual precipitation amounts decline.)



precipitation as normal. However, December of 2003 saw a steady procession of storms that delivered above normal precipitation amounts. Overall, both the northern and southern portions of the Basin experienced a normal number of precipitation days but less than normal amounts of precipitation during the winter season. The number of precipitation days in spring was well above normal (particularly for April) but the amount of precipitation during the spring was slightly above normal. Precipitation during the summer was spotty due to the absence of strong frontal storms and the occasional development of isolated thunderstorms. Overall, the frequency and amount of precipitation during the summer was near normal. Precipitation in the fall however was about half of normal both in terms of frequency and amount. Of course, it should be remembered that although the frequency of frontal storms typically increases in November, the frequency and total amount of precipitation during the fall season is

Figure 2-2. Map Showing Locations of Selected Meteorological Sites in the Vicinity of Lake Tahoe.

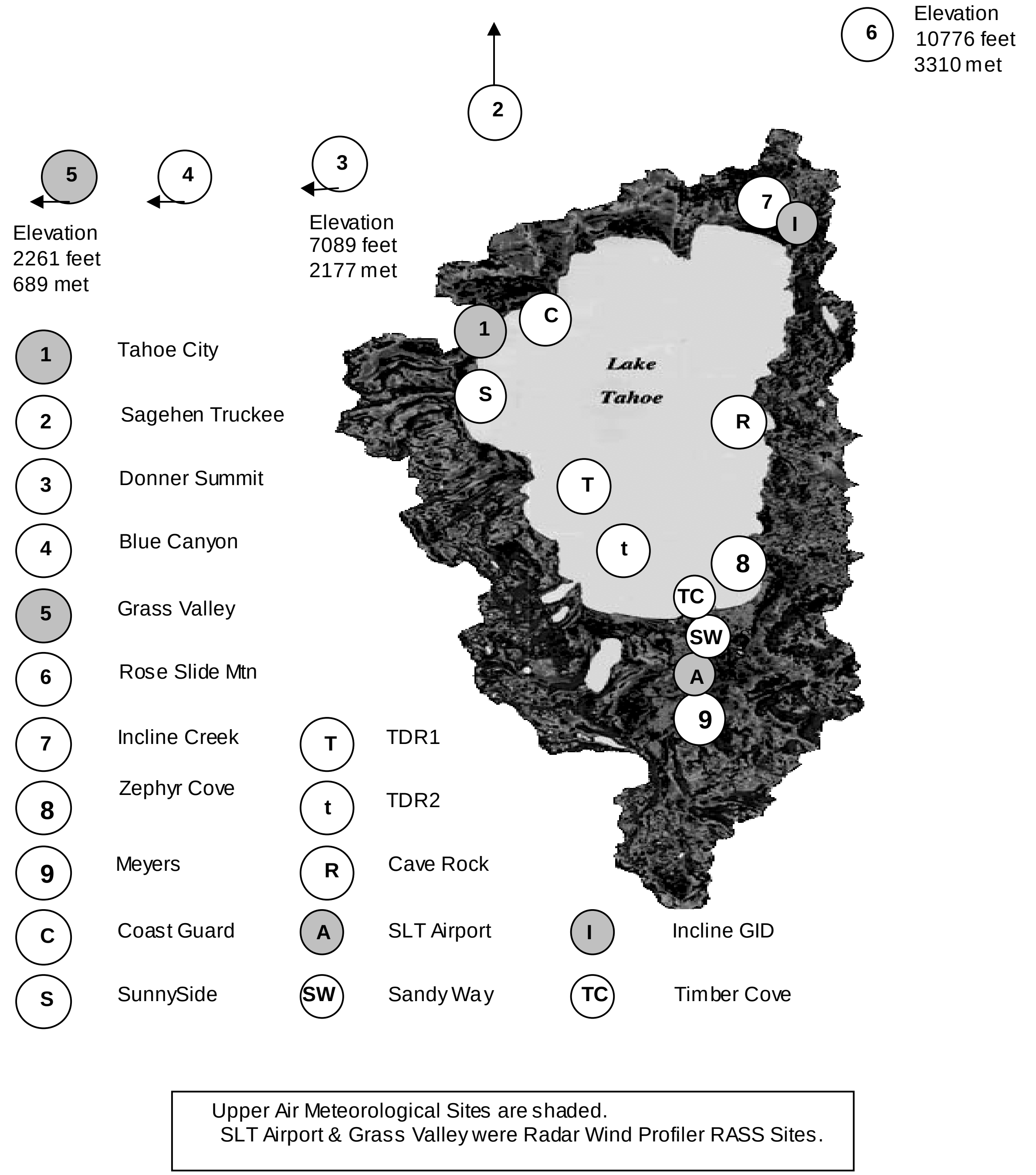
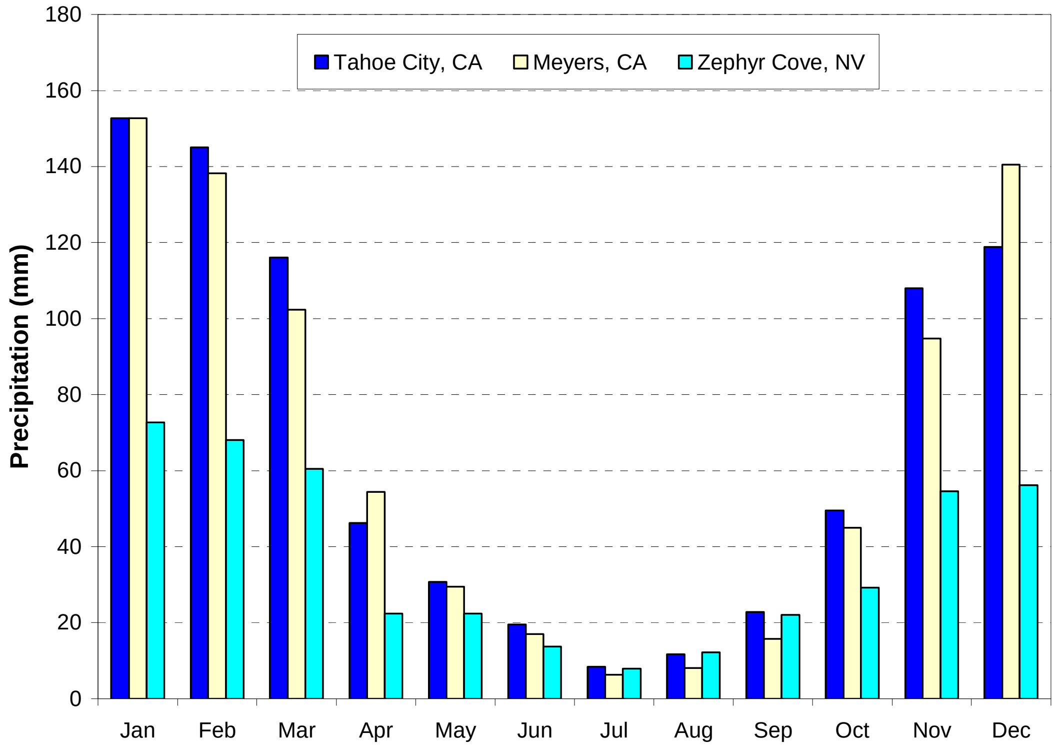


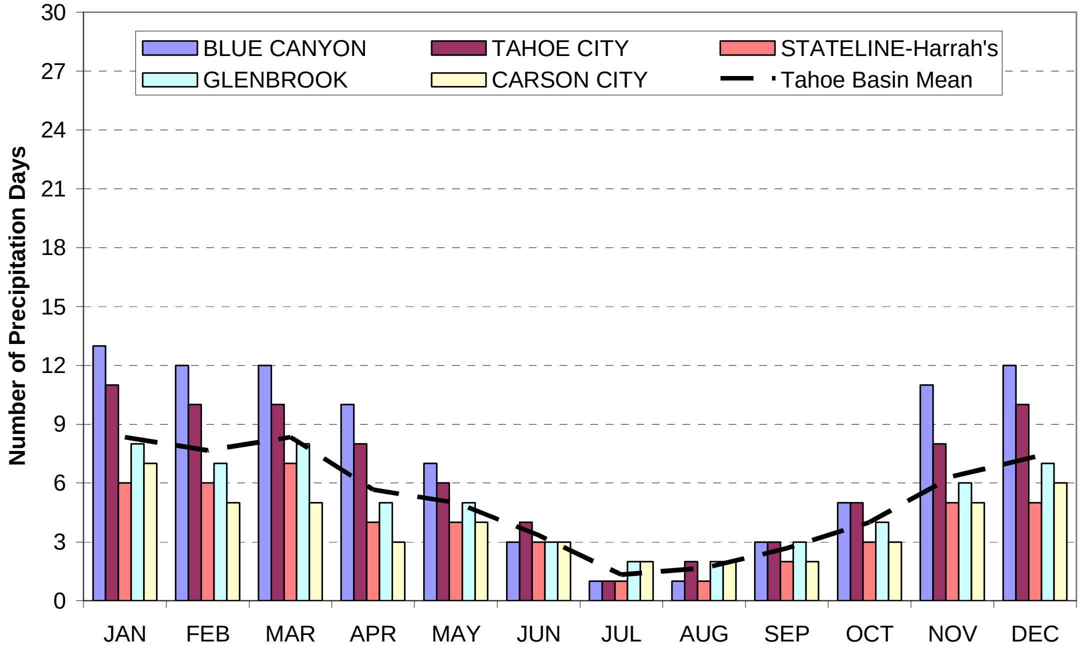
Figure 2-3. Long-term (≥ 30 years) Monthly Mean Precipitation Amounts in Lake Tahoe Basin.
(Source: AccuWeather, 2004)



relatively limited – significantly greater than in summer but still significantly less than in winter and even spring.

When the precipitation frequencies during 2003 at Incline Creek and Meyers are compared with the Tahoe Basin norm (developed in **Figure 2-4**), it can be seen from **Figure 2-9** that the fall was drier than normal and that the precipitation frequency abnormalities in winter and spring were driven primarily by the frequent precipitation in December and April, respectively. Seasonal representations of normal precipitation frequencies and the frequency in 2003 are shown in **Figures 2-10 and 11**, respectively. For the year, both Incline Creek and Meyers experienced about 45% <u>more</u> days of precipitation than normal despite precipitation amounts being less than normal. Thus, the 2003 wet deposition estimates will also be higher than normal. Based on the number of days with measurable precipitation at Meyers and Incline Creek in 2003 compared to normal in the Tahoe Basin, wet deposition in a year with a normal precipitation frequency could be as low as 70% of the 2003 values reported in Chapter 5. However, the exact discount amount for a year with a "normal" precipitation frequency would depend not only on the seasonal precipitation frequencies but would also be ameliorated by the higher precipitation frequency likely causing lower ambient concentrations.

Figure 2-4. Normal (long-term average) Precipitation Frequencies (# of days with precipitation > 0.01 inches) at Selected Near-Tahoe Locations* in the Sierra Nevada.



*** Note:** Precipitation data are no longer collected at Stateline, NV (mean is based on 1984-98 data). Precipitation data for Glenbrook, NV (in-basin) and Carson City, NV (outside of Tahoe Basin) represent 1948-2005 means. Additional hourly or summarized meteorological data for these sites were not accessed or retrieved for LTADS.

Figure 2-5. Precipitation Frequencies (# of days with precipitation > 0.01 inches) during 2003 at Selected Near-Tahoe Locations in the Sierra Nevada. (Source: WRCC, 2005)
(Note: the long-term (30-year) annual mean precipitation amounts are shown in parentheses.)

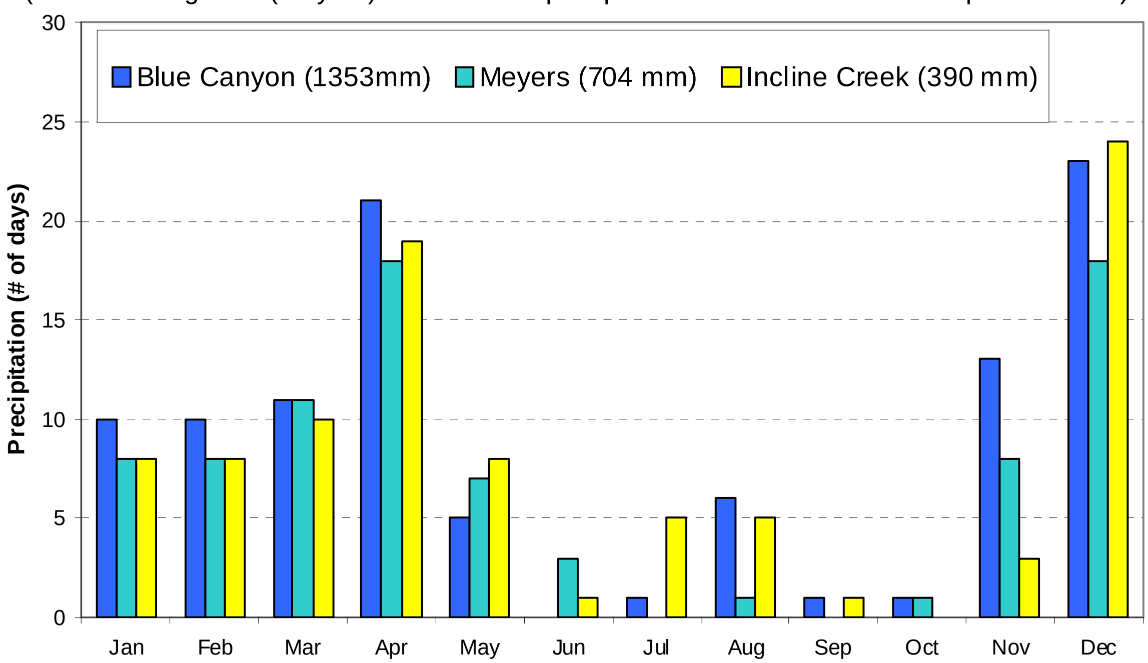


Figure 2-6. Hourly Precipitation Amounts at Incline Creek in 2003.

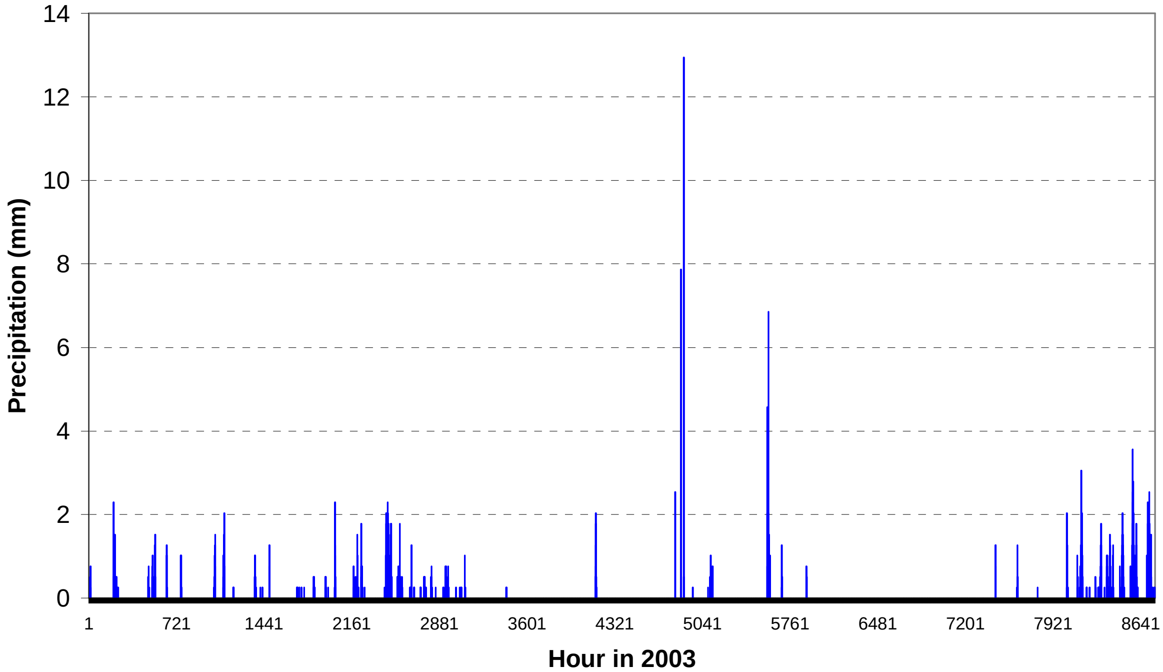
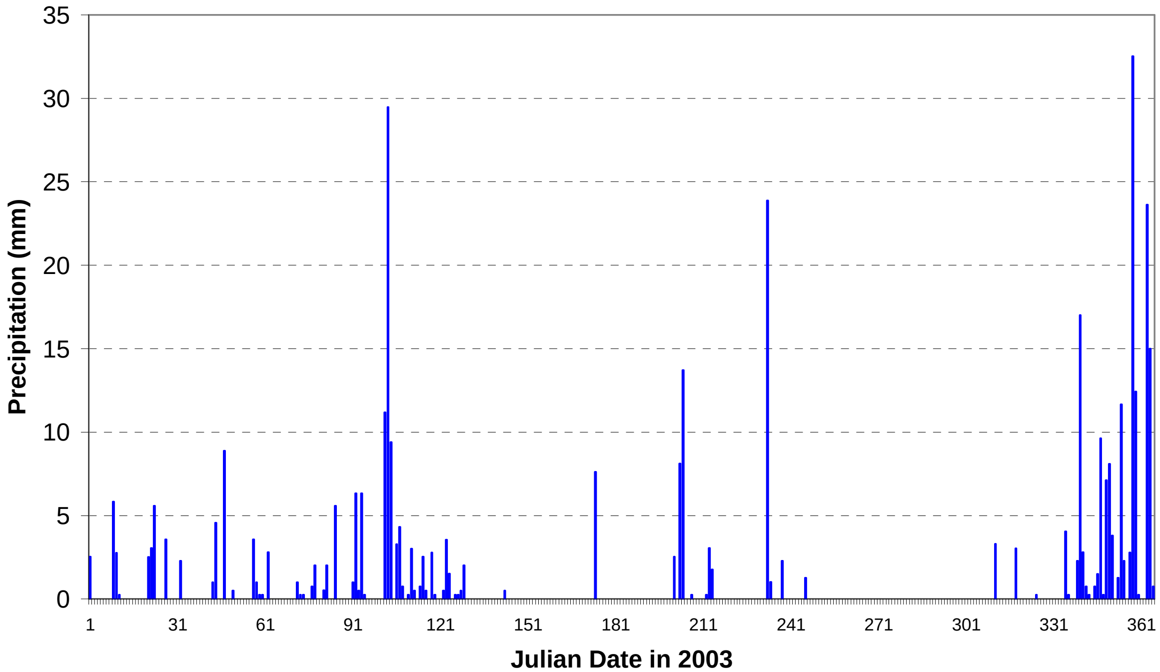


Figure 2-7. Daily Precipitation Amounts at Incline Creek in 2003.



What might all of this mean with respect to atmospheric deposition in 2003 compared to an average (climatologically normal) year? More frequent storms would tend to decrease pollutant concentrations by increasing turbulence and atmospheric mixing. However, increased turbulence could also increase the dry deposition rate of gaseous pollutants that are water soluble (e.g., ammonia and nitric acid). Wet deposition, on the other hand, would always be expected to increase with increasing frequency of precipitation. As indicated in **Figure 2-8**, the number of days with precipitation (≥0.01") was almost twice normal for the winter and spring seasons, approximately normal for the summer, and almost half normal for the fall. Overall, 2003 experienced about 50% more precipitation days than in the average year (~90 vs. 60). Because atmospheric mixing is reduced during winter (except during storms) and pollutants are trapped near ground-level by frequently occurring surface inversions, the staff's dry deposition estimates for winter could be lower than in average years due to likely lower ambient concentrations than normal as a result of the more frequent storms. On the other hand, this potential underestimation of dry deposition is partially offset by staff not discounting the dry deposition during the periods of precipitation when ambient concentrations would be lower than the seasonal average. The wet deposition estimates might not be affected significantly because the estimate is based on the product of concentrations and precipitation frequency. Thus, the wet deposition increase due to more frequent precipitation would be counter balanced by the lower concentrations (amount of material) available for wet deposition.

Figure 2-8. Precipitation Amounts in 2003 versus Seasonal Normals.

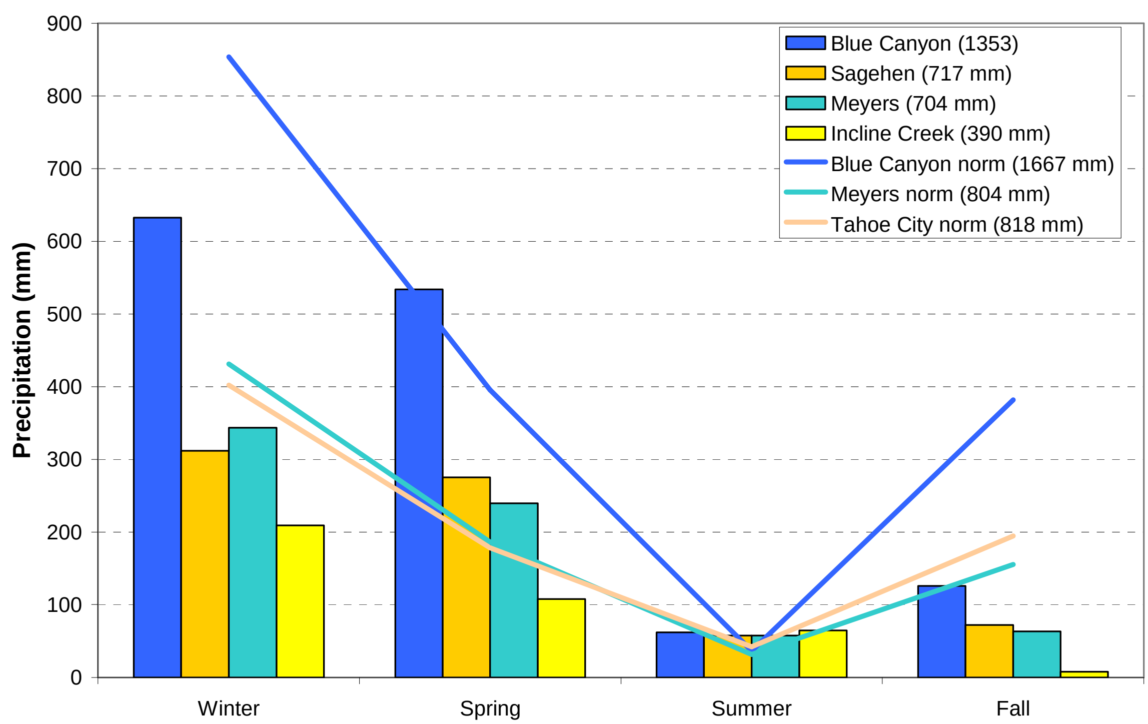


Figure 2-9. Comparison of Precipitation Frequencies (# of days with precipitation > 0.01 inches) during 2003 at Two Tahoe Locations with the Climatological Mean for the Tahoe Basin. (**Note:** Tahoe Basin mean is based on long-term results for Stateline (1948-1998), Glenbrook (1948-2005), and Tahoe City (1914-2005).)

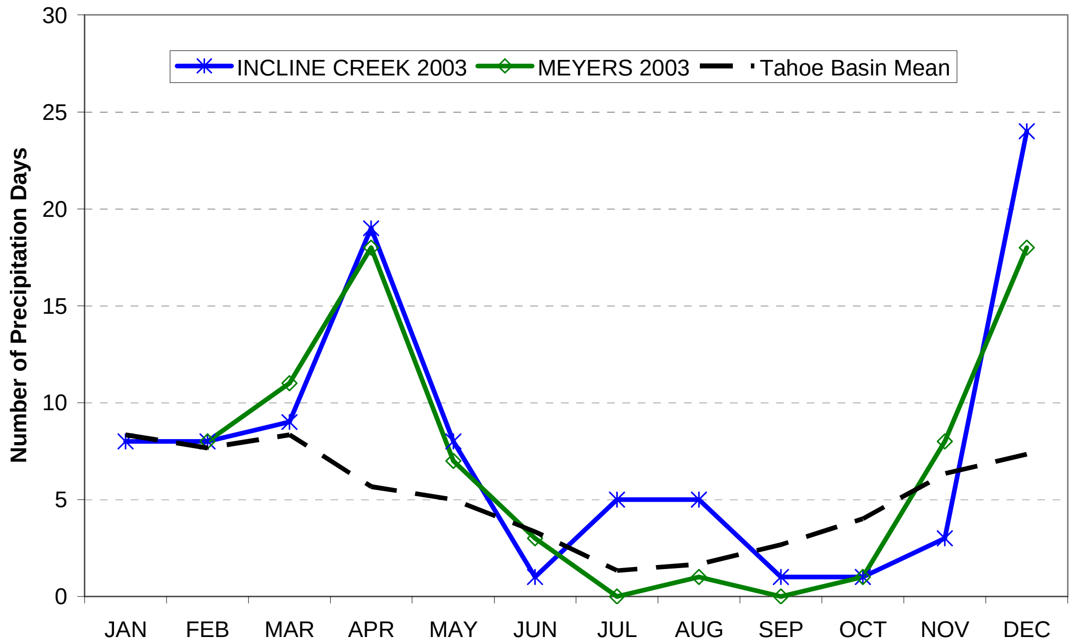


Figure 2-10. Climatologically Normal Number of Days per Season with Precipitation Amounts greater than 0.01 inches. (Note: Tahoe Basin mean is based on long-term results for Stateline (1948-1998), Glenbrook (1948-2005), and Tahoe City (1914-2005).)

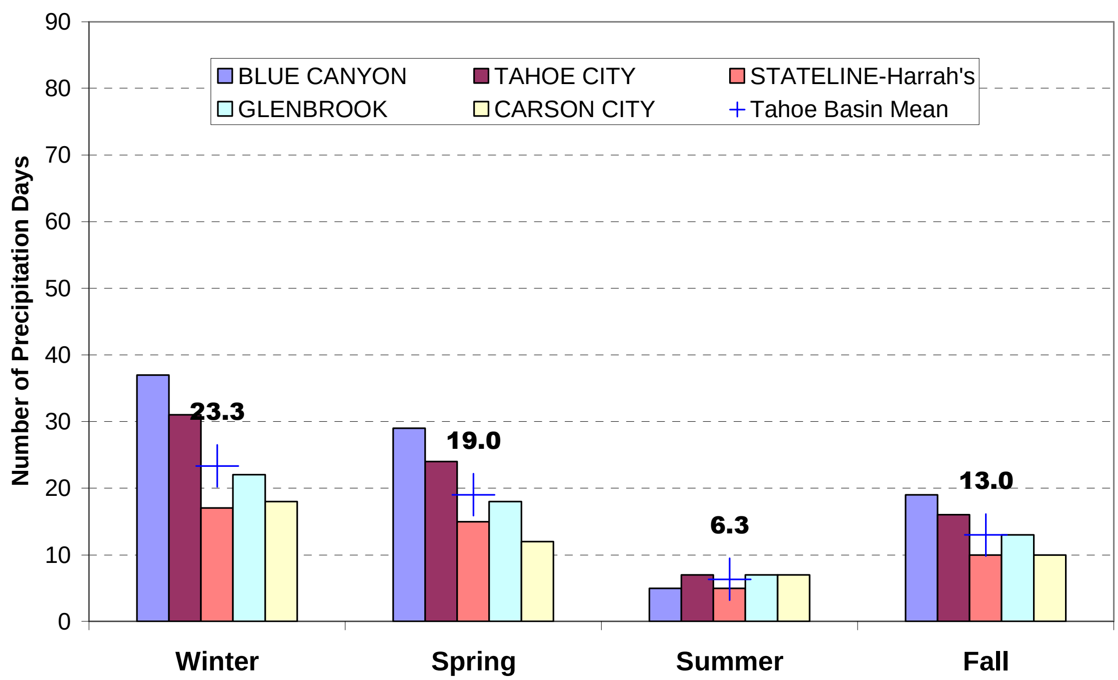
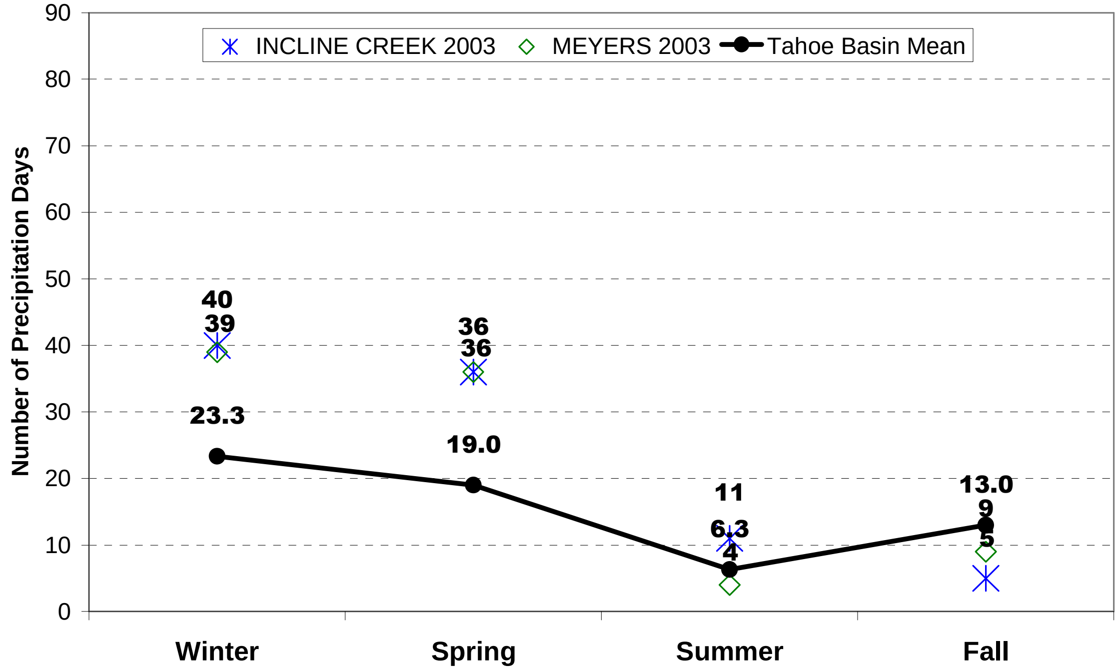


Figure 2-11. Comparison of 2003 against Climatologically Normal Number of Days per Season with Precipitation greater than 0.01 inches. (**Note:** Tahoe Basin mean is based on long-term results for Stateline (1948-1998), Glenbrook (1948-2005), and Tahoe City (1914-2005).)



2.2 Temperature Patterns

The distinctive patterns of temperature in the Tahoe Basin provide a framework for broad understanding of horizontal winds and vertical mixing, and their variations by time of day and season. The winds, obviously responsible for horizontal transport of any pollutants, water vapor, or nutrients that they contain, are driven primarily by gradients of air density and air pressure. Those gradients are caused by the differences in air temperature that will be described here. Furthermore, the variation in air temperature with altitude above the ground or water surface is critical to the vertical dispersion of pollutants.

Thus, temperature patterns provide a foundation for understanding the potential for transport and dispersion, and ultimately deposition of substances emitted into the atmosphere. Likewise, because those temperature patterns give insight into the potential for horizontal and vertical movement of atmospheric constituents, they also provide insight into the likely spatial representativeness of the observed concentrations that will be described in Chapter 3. The next sections describe the patterns of temperature, and their implications for locally generated winds and for enhancing or suppressing vertical mixing.

2.2.1 Surface Air Temperatures

As illustrated in **Figures 2-12 through 2-14**, average temperatures near lake level in the Tahoe Basin in the summer (July) range from daily maximums in the low 80s (^{O}F; ~28 ^{O}C) to daily minimums in the 40s (^{O}F; ~7 ^{O}C); in the winter (January), temperatures range from highs around 40 ^{O}F (4 ^{O}C) to lows around 20 ^{O}F F (-7 ^{O}C). The diurnal ranges in temperature in July are about 30 ^{O}F (17 ^{O}C) (at Zephyr Cove (east), 35 ^{O}F (19 ^{O}C) at Tahoe City (northwest), and 40 ^{O}F (22 ^{O}C) at S. Lake Tahoe (south). The diurnal variations in temperature during January are smaller, 20 ^{O}F - 25 ^{O}F (~12 ^{O}C) (greatest at S. Lake Tahoe). In general, temperatures decrease with increasing altitude but local temperatures also depend on humidity, exposure to sunlight, and terrain-following air flow.

Figure 2-15 provides a daily trace of the maximum and minimum temperatures during 2003 at the ARB air quality monitoring site in South Lake Tahoe. The dominant feature, particularly from the daily maximum temperature trend, was the rapid transitions between winter and summer. The effect of the stormy April is also evident. In general, the difference between the daily maximum and daily minimum temperatures are greater during dry periods (e.g., summer) and little smaller during wet periods (e.g., December). However, when the temperatures in 2003 are compared to the monthly climatological temperature norms for sites around the Basin (**Figure 2-16**), 2003 appears quite normal except for the months of April and November, which were cooler than typical, and January, which was slightly warmer than normal. Because the deposition estimates are made on the basis of seasonal air quality and meteorological conditions, the seasonal temperatures for 2003 are compared with seasonal norms in **Figure 2-17**. Once again, the 2003 temperatures appear representative of typical temperatures experienced in previous years.

Figure 2-12. Monthly Mean and Record Temperatures at Zephyr Cove, NV.
(Source: AccuWeather, 2004)

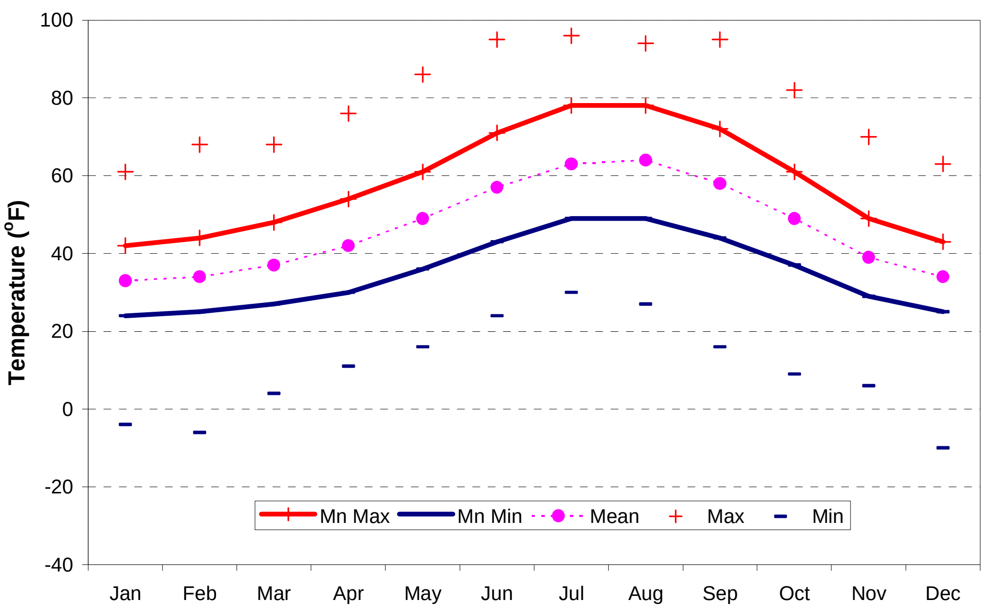


Figure 2-13. Monthly Mean and Record Temperatures at Tahoe City, CA.
(Source: AccuWeather, 2004)

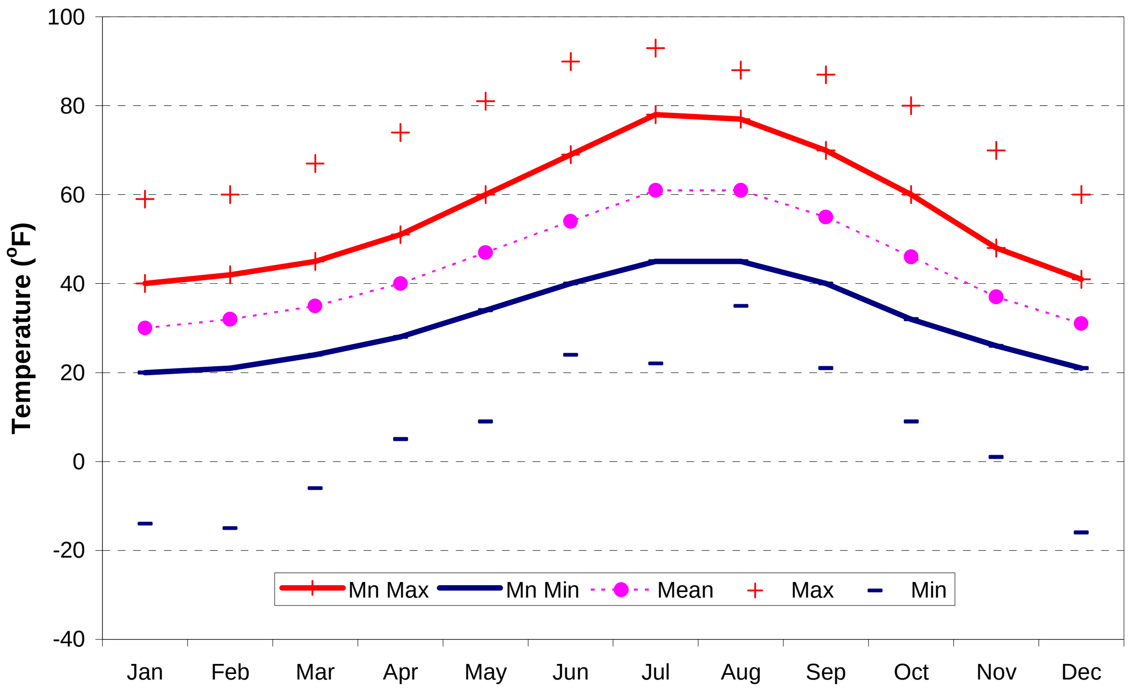


Figure 2-14. Monthly Mean and Record Temperatures at South Lake Tahoe, CA.
(Source: AccuWeather, 2004)

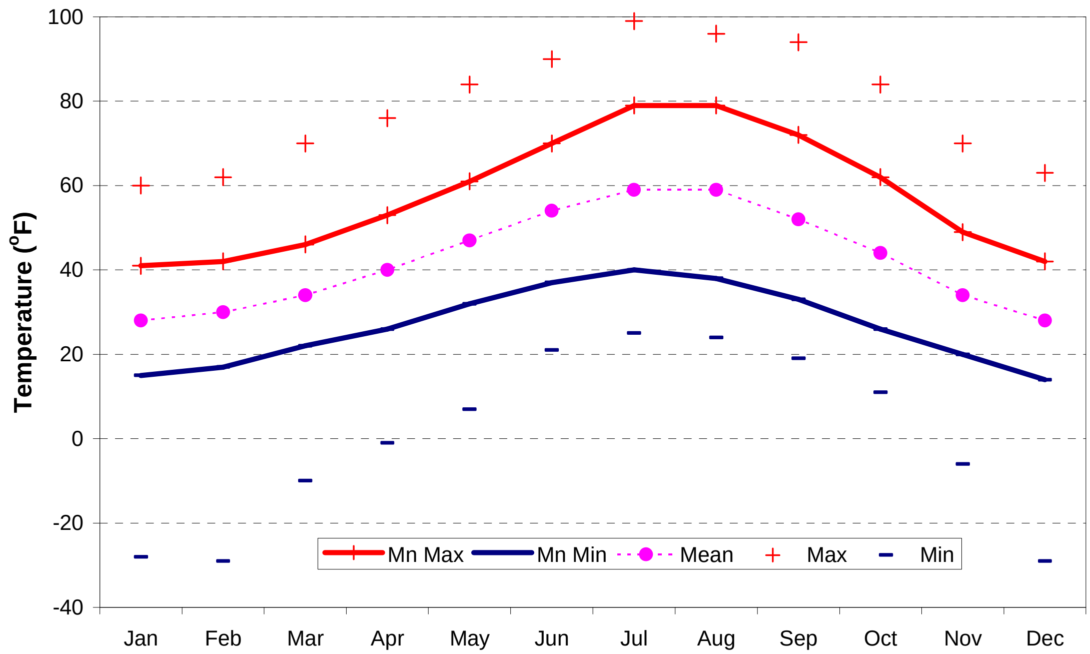


Figure 2-15. Daily Maximum and Minimum Temperatures during 2003 at South Lake Tahoe (Sandy Way).

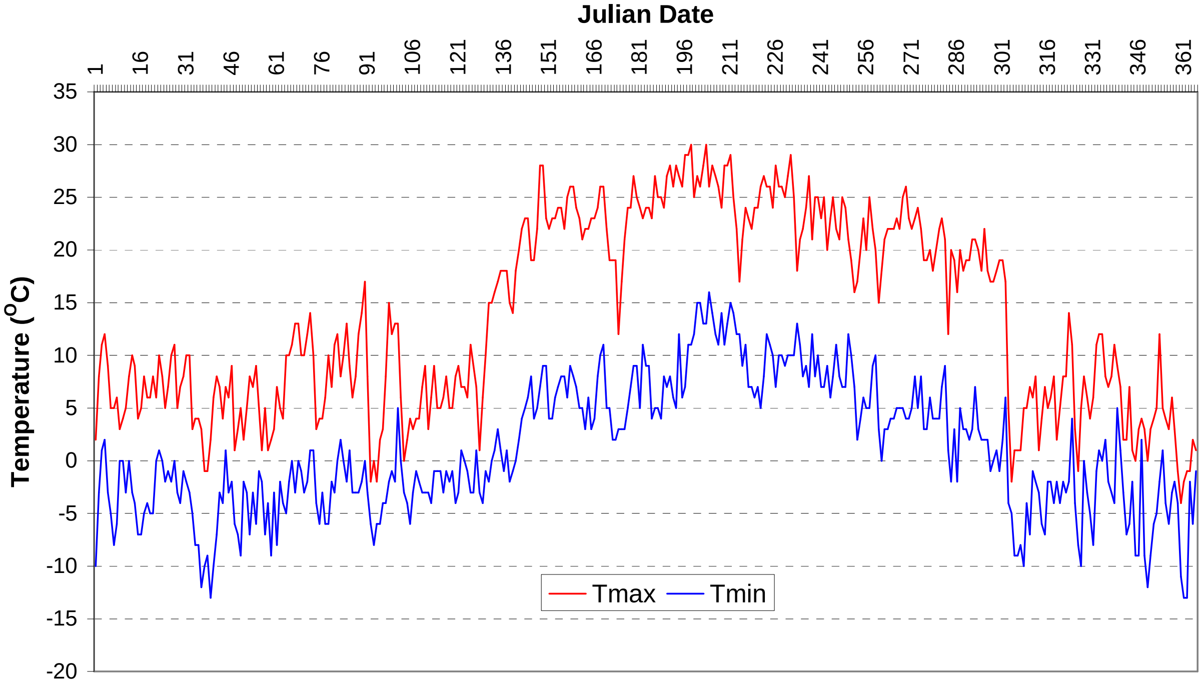


Figure 2-16. Comparison of 2003 Temperatures at SLT – Sandy Way with Climatological Normal Temperatures at Long-Term Sites in the Tahoe Basin.

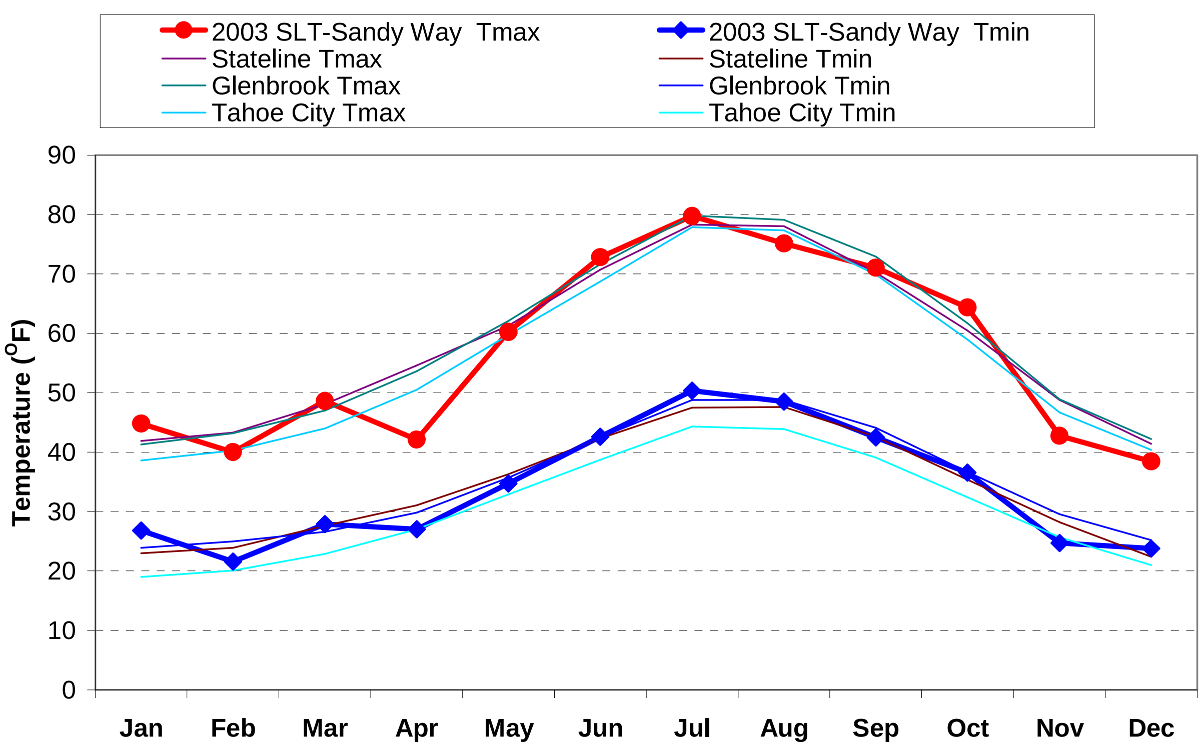
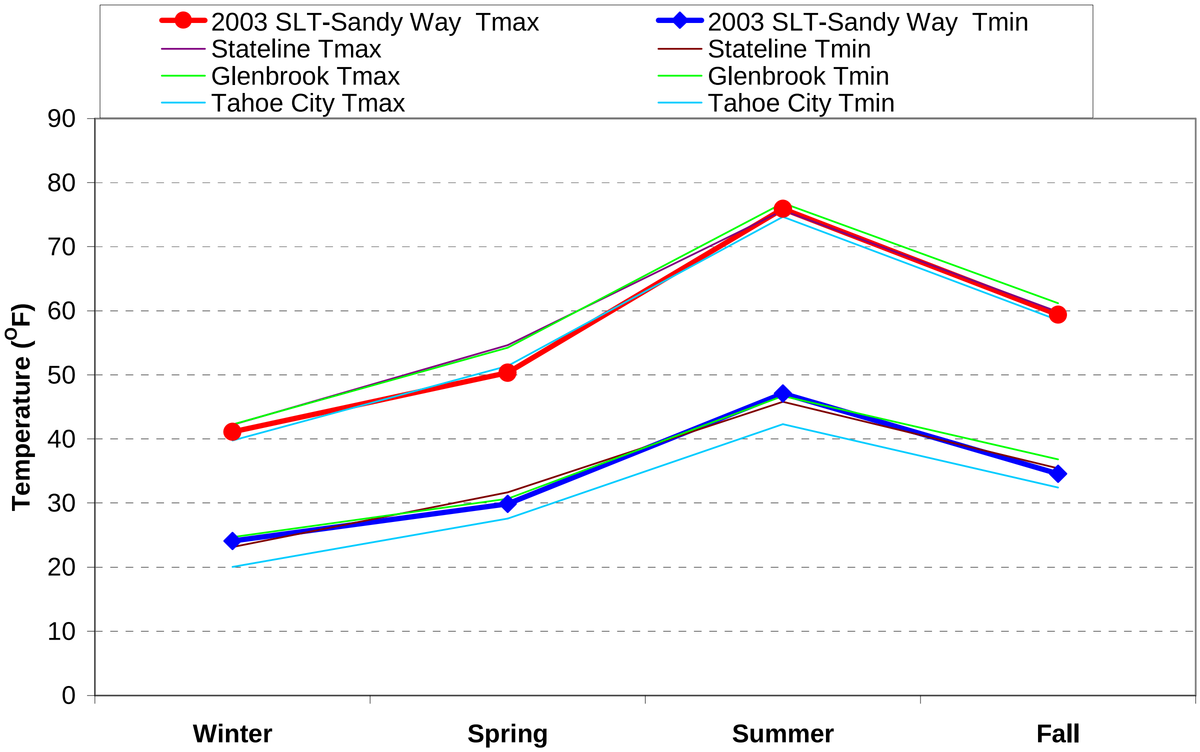


Figure 2-17. Comparison of Seasonal 2003 Temperatures with Seasonal Normals.



With increasing altitude, the air is less dense and holds less water vapor, two factors that help air retain its heat. Land surfaces at altitude cool rapidly at night and thereby also cool the lowest layer of the atmosphere. Because cold air is heavier (more dense) than warm air, the bowl-like shape of the Basin facilitates the accumulation of the cold air draining off the mountain slopes. Thus, nocturnal temperature inversions frequently form during all seasons and have great potential to accumulate air pollutants (Twiss et al., 1971). The months of June through October have the most frequent inversions, averaging 15 to 20 days per month. Surface-based inversions influence when and how deeply local emissions are mixed vertically and diluted (assuming cleaner air aloft, away from local emissions). In addition, temperature inversions inhibit vertical mixing between air aloft (that may transport material over the mountains) and the surface air that is in contact with the ground and water surfaces.

Due to the alpine location of the basin, the greater intensity of solar radiation relative to lower elevations has the potential to accelerate ozone and nitrogen photochemistry (Twiss et al., 1971). Generally more solar radiation reaches the Lake Tahoe Basin because the thinner and less polluted atmosphere scatters and absorbs less solar radiation. However, although scattering and absorption both tend to decrease the incident radiation at the surface, they may have opposite effects on rates of photolysis because those rates depend not on the incident radiation (i.e., on a surface) but on the actinic flux. The actinic flux is the spherically integrated radiative flux (i.e., the sum of the incoming radiation from any and all directions) that is intercepted by each atmospheric molecule. Although absorption decreases both incident radiation and actinic flux, generally scattering decreases incident radiation but increases actinic flux. The relative changes in the actinic flux and resulting rates of photolysis depend on the size and chemical composition of particles and their vertical distribution.

2.2.2 Vertical Distribution of Temperature

A layer of the atmosphere in which the air temperature increases with height is an effective barrier to vertical mixing. Such a layer (referred to as a temperature inversion or thermally stable layer) is typically caused by various predictable and observable atmospheric processes. If observations are available, layers with or without vertical mixing can be differentiated by examining how the temperatures change with altitude above the surface and by comparing observed air temperatures near the surface and with those aloft.

Temperature inversions (in the most simple sense, where warmer air overlies cooler air) greatly restrict the exchange of air and the pollutants between the different layers. Inversions can be formed by a variety of methods – subsidence (sinking air associated with high pressure systems), advection (e.g., sea/lake breeze), radiative cooling, cold air drainage, etc. Inversions that form at ground level are of particular interest as they will trap most pollutant emissions and keep them near ground level where people can be impacted by them and where surfaces are available for deposition.

2.2.2.1 Subsidence Inversions

A region of high pressure generally creates a temperature inversion aloft (as a result of subsiding air) and thereby restricts vertical mixing across the subsidence inversion. The position and strength of the eastern Pacific high pressure zone varies seasonally and daily, and thus it has an intermittent effect on temperatures aloft and vertical mixing of the atmosphere over the western states including the Tahoe Basin. The restriction of vertical mixing due to the Eastern Pacific High is generally greatest in the late summer and early fall. When present, the area of high pressure creates divergent (i.e., net outward) horizontal air flow over a broad area (i.e., spanning hundreds to thousands of kilometers) and continuity of mass requires a compensating weak downward motion of the air aloft in response. Intuitively, one might expect downward motion of the air aloft to cause downward mixing of air from aloft, but it does not. The downward motion is very slow and thus extends only very short vertical distances, but it creates a persistent temperature inversion near 9-10 thousand feet MSL. As the air moves downward, it is compressed by the increasing air pressure it encounters and is heated by that compression. Thus, the Eastern Pacific High can create a relatively persistent temperature inversion over a large area that is an effective barrier to vertical mixing of surface air with air above it.

Some subsidence and heating of air is also expected in the lee of the Sierra crest and that downward motion will also induce compressional heating of a layer of air and possibly generating another temperature inversion. However, a lee inversion would likely be of limited spatial extent and may only intermittently block vertical mixing. Also, it is common for shallow atmospheric waves to develop in this inversion layer that are analogous to water waves. The atmospheric lee waves may intermittently cause mixing of air above and below the inversion. However, observations relevant to documenting such processes were outside the scope of LTADS.

Another weak type of subsidence inversion occurs (primarily in the summer and fall) when winds are weak and the solar heating of the land draws air off the Lake and up the mountain slopes. The air moving off the Lake is replaced by descending air above which warms due to compressional heating. This descending air can evaporate haze and fog layers from above while creating a subsidence inversion trapping particles and other pollutants below it. Again however, observations relevant to documenting such processes were outside the scope of LTADS.

2.2.2.2 Surface-Based Inversions

Surface processes are also important to determining vertical mixing and their effects vary over smaller areas. In considering mixing depths in the Tahoe Basin, it is especially important to understand the processes that may cause the mixing depth to differ over the Lake as compared to over the land.

The typical diurnal evolution of the surface mixing depth over land is discussed first. Over land at night and in the early morning, there is usually only shallow vertical mixing (especially with clear sky conditions) because a surface-based inversion forms due to radiative cooling of land surfaces and advection (e.g., drainage of cooler air off the mountain slopes). Around sunrise, it is common for concentrations of pollutants at the surface to be relatively high because local emissions (e.g., from wood combustion or traffic) are usually mixed only through a shallow layer of air. Under these conditions (especially with light winds and a low sun angle), it is frequently possible to visually observe a relatively polluted surface layer and a sharp transition to cleaner air above the inversion.

As the ground is heated by the sun, the air at the land surface is warmed; over flat areas, the depth of mixing increases while upslope flows are generated in more complex terrain. Frequently, it is possible to visually observe the depth of the surface layer increase during the morning hours as land surfaces are heated by the sun and in turn heat the lower atmosphere. As the mixing depth increases through the day, pollutants emitted at the surface are diluted through a deeper volume and concentrations at the surface generally decrease. However, it is also possible for higher concentrations of some pollutants to occur above the mixed layer. In this case, the increasing depth of the mixed layer of air near the surface will mix some of the air aloft into the surface layer and the resulting concentrations will reflect a mixture of the concentrations previously observed at the surface and aloft.

By mid-day, vertical mixing can be vigorous through a moderately deep surface layer as the sun warms the ground and the air in contact with the ground, creating thermal plumes that rise until they reach a layer of warmer air aloft. The maximum depth of the surface mixed layer usually occurs approximately the time of daily maximum air temperature at the surface, typically between 1300 and 1600 local time. As the sun drops toward the horizon, the earth's surface and the air near it, begin to cool and over a period of hours (and generally before sunset), a nocturnal surface-based inversion is formed. The surface cooling typically begins before sunset because the net radiation balance at the surface becomes negative before sunset (as the incoming short-wave solar radiation decreases quickly and outgoing long-wave infrared radiation decreases slowly).

Thus, over land with clear skies, periods of vertical mixing through moderate or deep layers are generally limited to the daylight hours and mixing is deepest from about noon to mid-afternoon. Clouds may moderate this cycle by decreasing both daytime heating and nocturnal cooling of the ground surface. Deep mixing will also be present over both land and water during the passage of low-pressure storm systems, the formation of cumulonimbus clouds, and possibly the presence of high winds.

2.2.2.3 Deep Mixing

During periods of deep mixing, concentrations are generally low both at the surface and aloft. Deep vertical mixing occurs during the passage of low-pressure storm systems. Deep mixing will also occur where cumulonimbus clouds develop (either with or without thunderstorms). High winds can also occur without a low pressure system or cumulonimbus and will generally disperse emissions and result in lower concentrations.

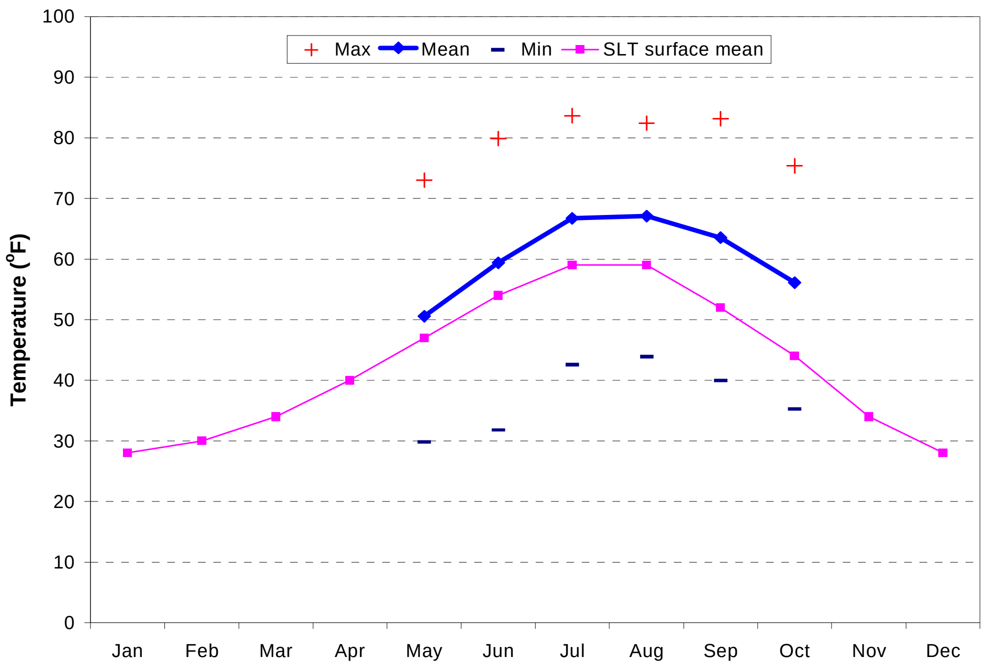
2.2.2.4 Differences in the Vertical Mixing of Air Over the Lake and Land

The vertical mixing of air over the Lake differs from that over the land because the day-to-night change in water surface temperature is small compared to that of the land surface. During most hours of the year, the temperature of the Lake water is warmer than the temperature of the air, with the greatest differential occurring at night and in the early morning. Thus, when cold down-slope drainage winds flow onto the Lake, we also expect some warming of air near the water and as a result, some vertical mixing due to weak convection. On the other hand, conductive cooling of the air by a colder Lake surface occurs during some seasons and hours, e.g., during summer mainly from mid-day to mid-afternoon. At these times, there is also a tendency for onshore flow so that the cooler air from over the Lake surface is advected over the land area, creating an inversion. However, such an inversion will likely not persist very far inland from the Lake due to heating of the land by the sun and enhanced mixing.

Rawinsondes, balloon-borne instruments for measuring temperature (humidity and winds aloft, are routinely launched at 00Z and 12Z (Zulu or Greenwich Meridian Time) from locations around the world. Zulu time is 8 hours ahead of Pacific Standard Time. Thus, the 00Z launch time corresponds to 1600 Pacific Standard Time (PST) of the prior day and the 12Z launch time corresponds to 0400 PST on the same day. The rawinsonde launch location in northern California is Oakland International Airport. Sondes are also launched at Reno, NV. Monthly mean temperatures observed at 00Z at the 850 millibar (mb) pressure level, about 4800 feet above mean sea level (MSL), above Oakland during the summers of 1991-2000 are plotted in **Figure 2-18**. Compared to temperatures observed at the surface, temperatures observed aloft are representative of those over a broad area. As one might expect, the temperatures over

Oakland at 850 mb are warmest during the summer and mean monthly temperatures exceed 60 ^{O}F (15.5 ^{O}C) during July, August, and September. Also shown in the figure are the monthly mean surface temperatures observed at South Lake Tahoe (6200 feet MSL). Comparison of the temperatures at South Lake Tahoe and at 850 mb pressure altitude over Oakland provides an indication of the seasonal tendency for temperature inversions (with inversions associated with relatively warmer temperatures over Oakland). Assuming a dry adiabatic lapse rate for the change in temperature with pressure altitude, the Oakland 850 mb temperature would be almost 5 ^{O}F colder at the elevation of Lake Tahoe. The temperature inversion analysis can be made by visually sliding the seasonal 850 mb temperature line downward 5 ^{O}F (to correspond to the equivalent temperature at the elevation of South Lake Tahoe). The tendency for warmer air over Oakland (and potential for subsidence-induced temperature inversions aloft over Tahoe) is lower in May and June, moderate in July and August, and greatest in September and October.

Figure 2-18. 850mb Temperatures at 4 a.m. PST at Oakland, CA. (Source: AccuWeather, 2004; Bennett, 2004)



A limited number of temperature soundings have been made over Lake Tahoe (Barone, 1979; Unger, 1979; Carroll, 2004). The data often indicate a subsidence inversion around 10,000 feet MSL and frequently another inversion is noted near 8,000 feet (') MSL (see **Figure 2-19**). Because most of the summer temperature soundings have been made with aircraft, less is known about the frequency and strength of low level (surface) inversions. Basic meteorological principles and the limited available information (e.g., balloons during winter) suggest that surface-based inversions may be quite common. Limited measurements of the mixing depths at the South Lake Tahoe Airport averaged 150 to 400 feet (Barone, 1979). An example of temperature profiles observed concurrently over land and Lake during a winter day is provided in **Figure 2-20**. In this example, a strong surface-based inversion is present in the morning over the Airport up to 7000’ with another inversion layer between 7250’ and 7750’. A couple of potential weak inversion layers might exist near 8000’ and 9600’. The subsidence temperature inversion is present from 10,500’ to at least 11,250’. Note that the morning temperature profile over the Lake indicates a surface-based inversion up to about 7500’ but it is much warmer and more isothermal than the surface inversion on land because the large thermal mass of the Lake moderates overnight decreases in air temperature. In the afternoon soundings, it is evident that solar heating and increased air movement raised the air temperatures throughout the atmosphere in the Basin. Although much weaker, temperature inversions still appear to be present at the surface and 7500’ at the Airport. Note too that the subsidence associated with a high pressure system also caused the base of the subsidence inversion to drop below 10,000’ during the day.

The LTADS aloft measurements included hourly remote sensing of temperature with the radar acoustic sounder system (RASS) operated in conjunction with the radar wind profiler at the South Lake Tahoe Airport. Although the RASS has less vertical range than the balloon borne rawinsondes, the ability to obtain hourly observations provides a great benefit for understanding the climatology of mixing in the Tahoe Basin. The data have been utilized by comparison of simultaneous hourly observations of air temperatures aloft (from the RASS) and near the surface as measured both at land sites and on the Lake itself.

Figure 2-19. Sample Temperature Profiles during Summer from Aircraft Soundings. (Unger, 1979)

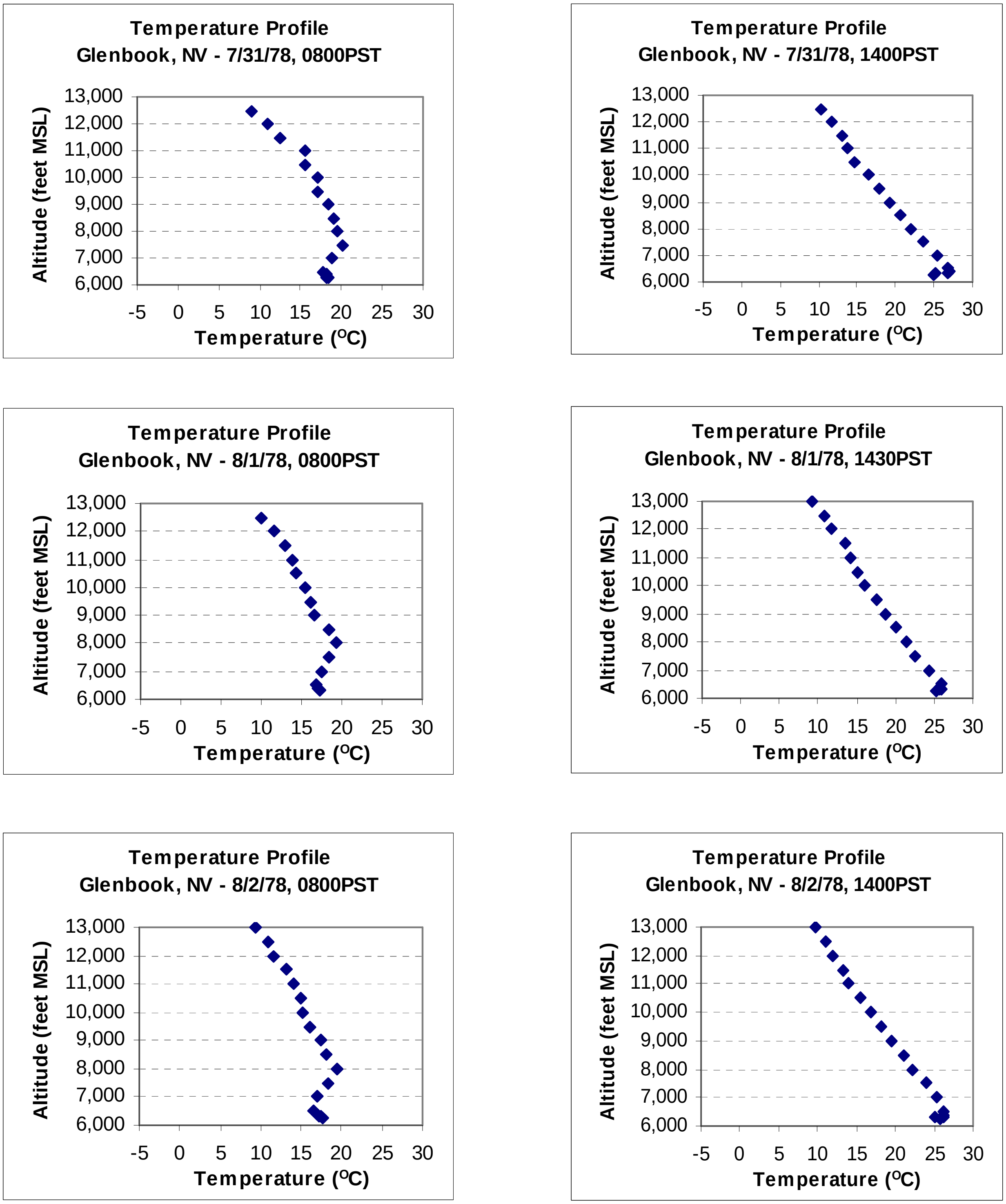
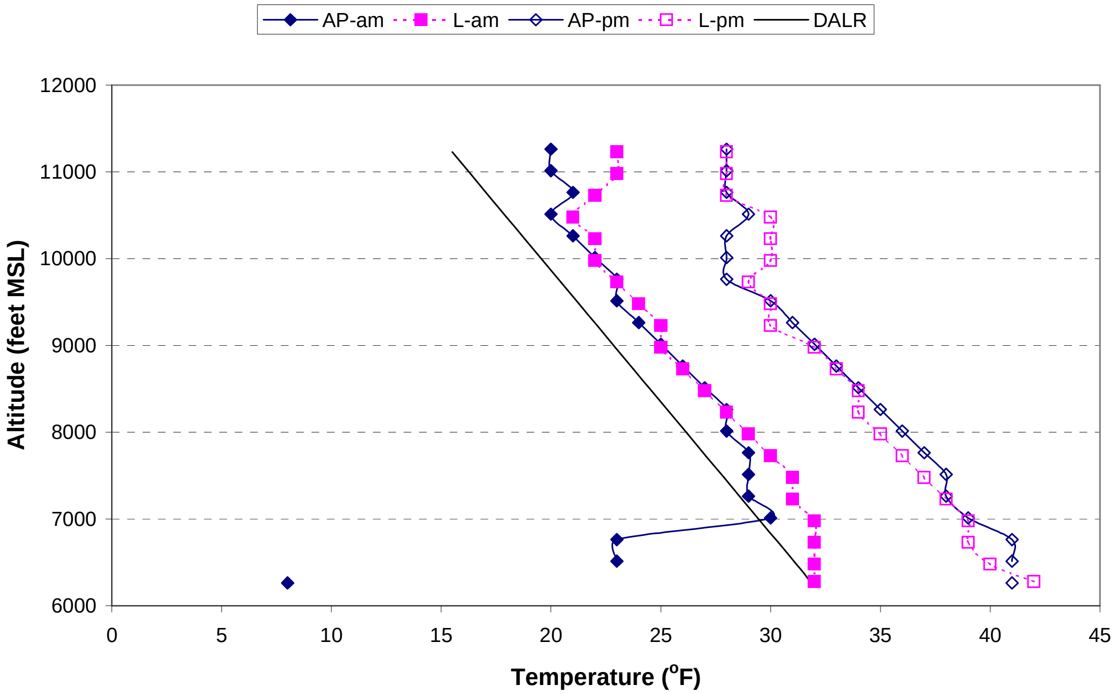


Figure 2-20. Sample Temperature Profiles During Winter (1/22/79) from Balloon Soundings Released in the Morning and Afternoon from the South Lake Tahoe Airport (AP) and from Lake Tahoe (L). (Unger, 1979)



Note: The dry adiabatic lapse rate (DALR) is shown as a solid straight line and indicates the rate that an air parcel would cool (warm) due solely to expansion (compaction) as the parcel might rise (descend) through the atmosphere. The parcel of air would tend to cease changing altitude when its temperature becomes the same as the ambient air around it. In general, a temperature inversion is present if the slope of the ambient temperature is greater (more vertical or even left to right) than the DALR slope.

2.2.3 Air and Water Temperatures

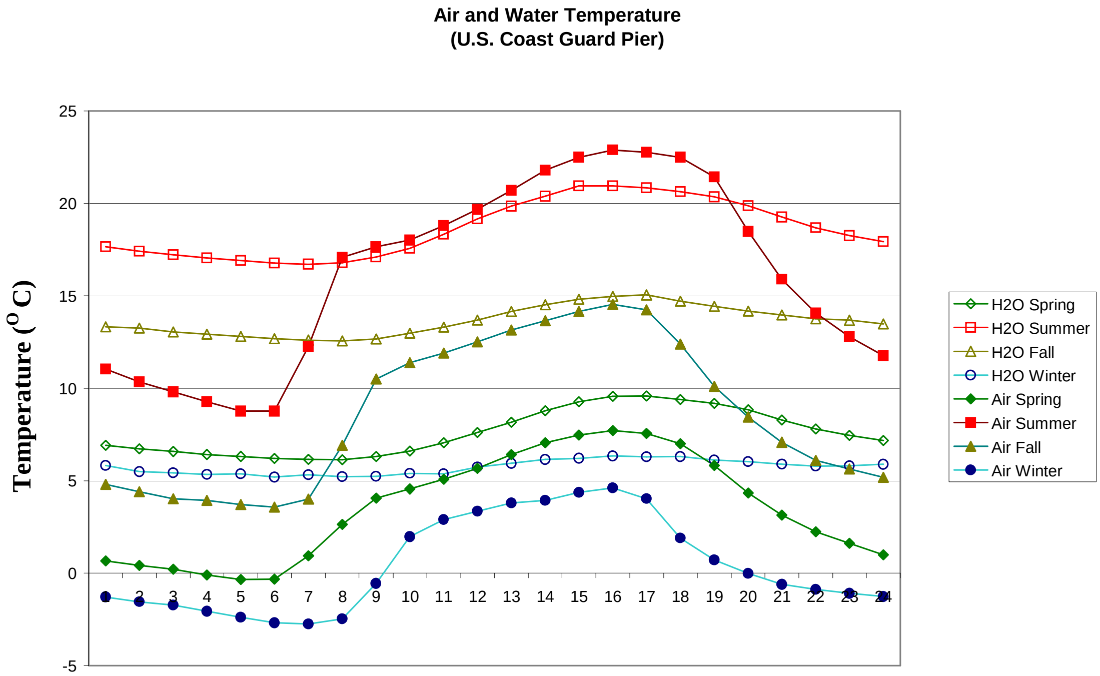
At Tahoe, because of the high altitude, steep terrain, and thermal inertia of the Lake, temperature patterns (and thus wind speed and direction) typically vary in predictable daily patterns. The thinner and often drier atmosphere at higher altitudes allows rapid cooling at night and results in larger day-night swings in land surface temperatures at Tahoe than at lower elevations. In contrast to the large temperature swings over land, the temperature of the Lake surface and the air temperature immediately above its surface are moderated by the large thermal mass of the deep Lake. Despite cold air temperatures during the night at altitude and sometimes deep snow fall, the depth of the Lake creates sufficient thermal inertia that the Lake surface does not freeze except for small areas near the shoreline and only during periods of extreme cold.

Figures 2-21 illustrate the seasonal average temperature of air (solid symbols) and water (open symbols) measured at 2-cm depth by time of day on Lake Tahoe. At the U.S. Coast Guard pier at night, during all seasons, the air is colder than the water temperature by about 6-8 ^{O}C. During fall and winter the air is colder than the water even during the warmest hours of the day. During spring and summer the air temperature exceeds the 2-cm water temperature during some daytime hours but by only a few degrees. Also note the very large increase in temperatures between the spring and summer seasons. In comparison to temperatures nearer the shoreline, the air temperatures observed 3 km offshore at the TDR1 buoy appear to be moderated by the Lake to a greater extent, but that moderation is also attributable in part to a lower measurement height. The TDR1 observations at 3 m above the Lake surface are about one half the height on the pier sites. As will be presented in Chapter 4, the air-water temperature difference is used as an indicator of atmospheric stability as part of the calculation of deposition velocity. **Figures 2-22** present the differences between observed air and water temperatures for the same sites.

The skin temperature of the water generally differs from the water temperature at 2-cm depth during relatively calm conditions, but the differences are small. The largest deviation will be under cloudless summer conditions due to stronger positive net radiation during the day and stronger negative net radiation at night.

Hook et al. (2003) discuss and plot bulk and skin water temperatures and associated meteorological variables at Lake Tahoe. Given low or moderate wind speeds (< 4 m/s), nighttime skin temperatures are cooler by 0.2 - 1.0 ^{O}C than bulk temperatures at 2-cm depth. Daytime skin temperatures can range from 0.2 ^{O}C cooler to >1.0 ^{O}C warmer than bulk water temperatures. The skin temperature is generally warmer than the bulk temperature as the net radiation approaches its maximum, and cooler than the bulk as net radiation decreases. During elevated (> 4 m/s) wind conditions, the difference between skin and bulk temperature can vanish, but will reappear within seconds of relaxation of the wind (Steissberg, 2005).

Figure 2-21. Seasonal Air and Water Temperatures at the U.S. Coast Guard Pier and TDR1 Buoy.



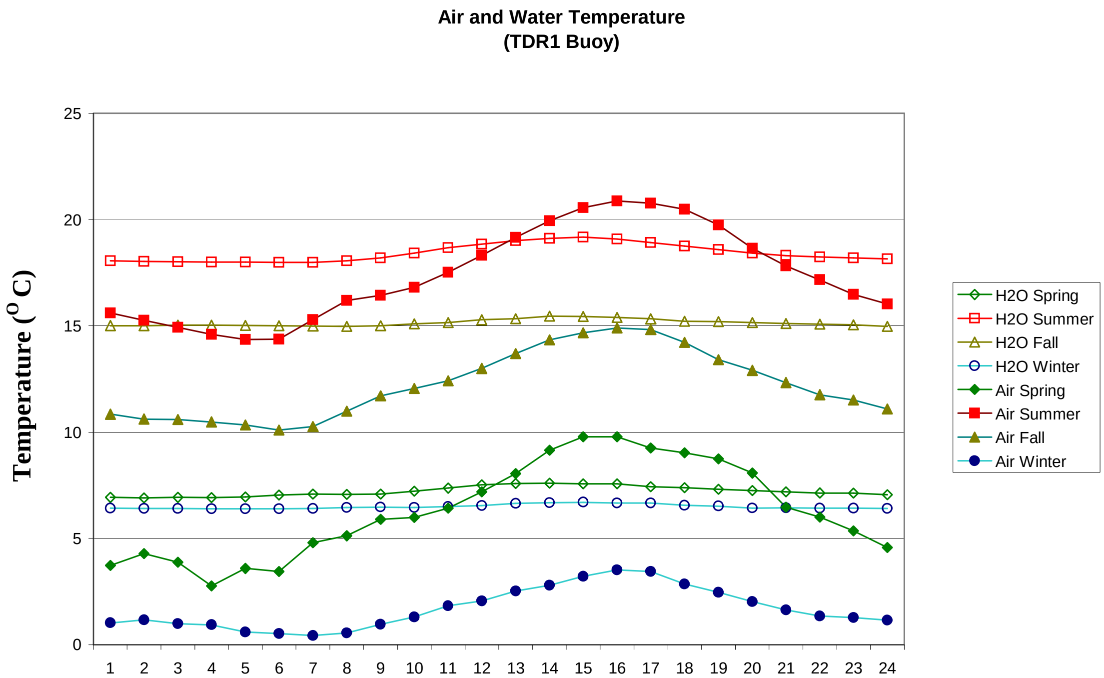
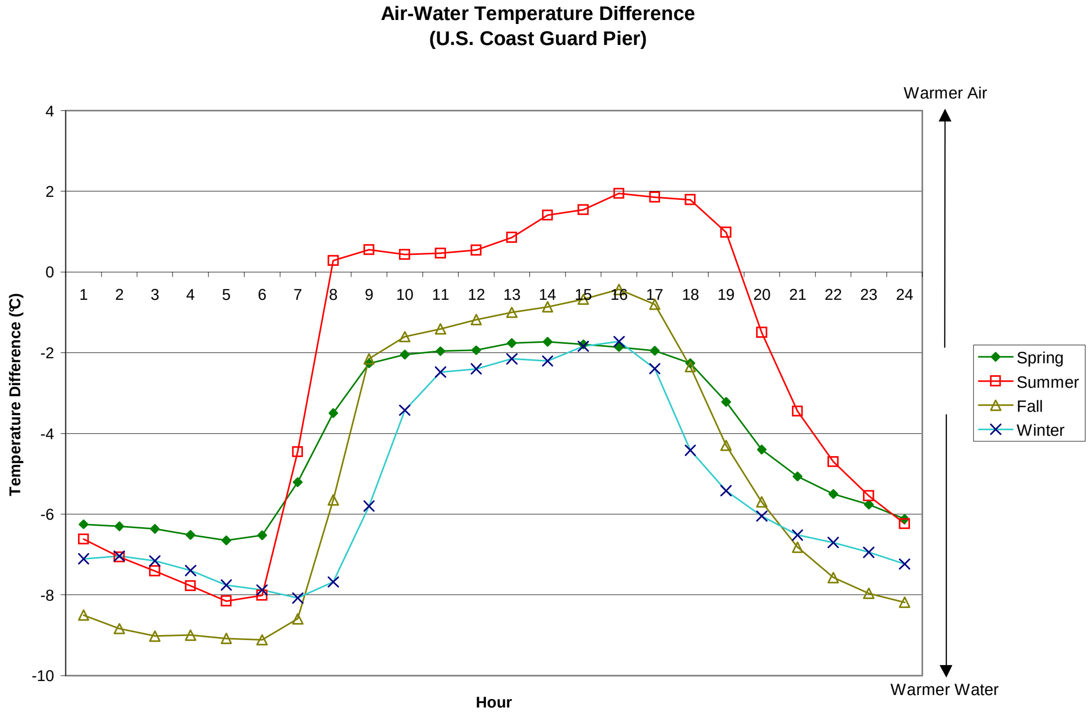
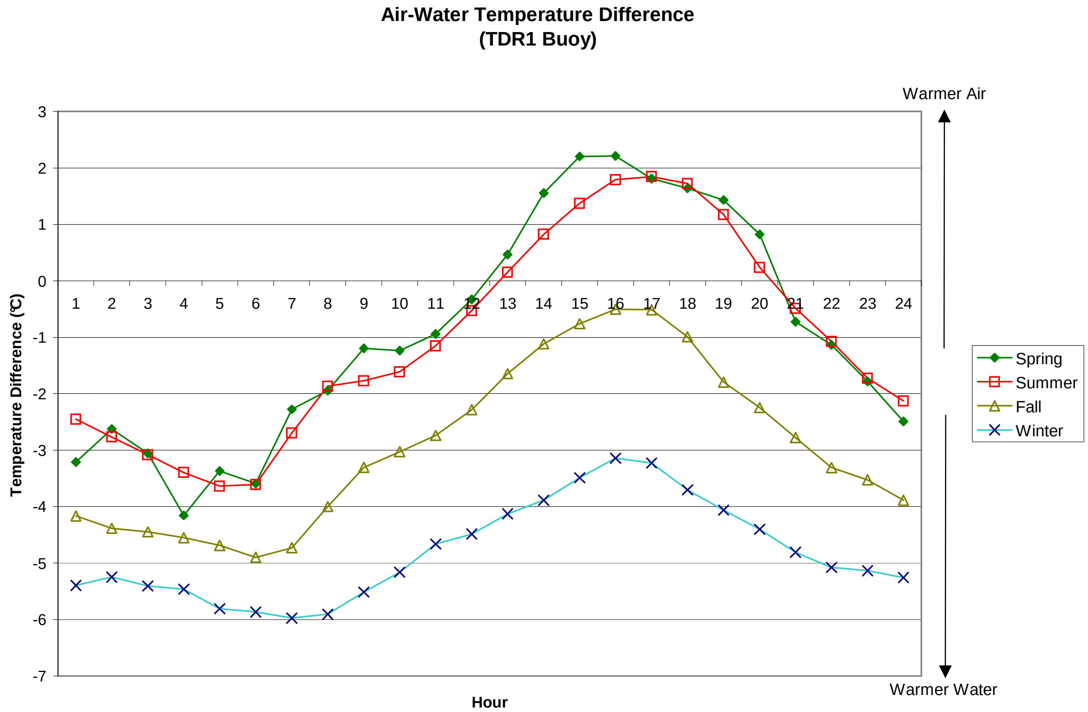


Figure 2-22. Seasonal Differences between Air and Water Temperature by Time of Day at the U.S. Coast Guard Pier and TDR1 Buoy.





The depth of atmospheric mixing is predicted from the simple concept that, when the surface air is cooler and denser than the air aloft, vertical mixing is suppressed. The comparison of surface and aloft temperatures allows determination of whether vertical mixing extends to the height of each of the range gates of the RASS during that hour. The comparisons require and included adjustments for differences in humidity and pressure elevation. The results can be summarized as the frequency of mixing to a given depth during any hour of day or season. **Table 2-1** presents estimated frequencies of mixing to the various range gate elevations based on hourly air and water temperatures at buoy TDR1 and air temperatures at Sandy Way. Consideration of these estimates should include review of the nature and limitations of the observations on which they are based, which are described below.

The RASS remotely measured average air density through 60-meter layers (range gates) and reported those densities as hourly values of virtual temperature, meaning the temperature of dry air having the observed density. Virtual temperature is a variable used by meteorologists to uniquely describe the density of air due to the combined influences of temperature and water vapor content. Because the air always contains some water vapor and the molecular weight of water is less than the average molecular weight of air, the virtual temperature is slightly higher than actual temperature. The RASS observed virtual temperatures for range gates spanning 90 to more than 1000 m above ground level (AGL). The lowest data recovery rates were in the higher range gates. Data recovery also suffered somewhat in the lowest (90-150 m AGL) range gate. The maximum range for collecting reliable temperature data averaged a little less than 1 km and varied depending on environmental conditions. Note also that there were seasonal differences in data recovery rates, with lower recovery rates for RASS data during summer. The variations in RASS data recovery rates for higher range gates and during certain periods are reflected in **Table 2-1** as “counts” of the pairs of valid surface and aloft observations used to estimate mixing at that elevation.

Because the comparisons of surface versus aloft temperatures were made with observations from different locations, it is also necessary to consider under what conditions the RASS observations are a reasonable representation of temperatures aloft over the surface sites. The RASS was located at SLT Airport nearly 5 km south of the Lake; Sandy Way is a few hundred meters from the shore; and TDR1 buoy is 3 km east of Meeks Bay. For hours of downslope flow the surface air temperatures at the airport and Sandy Way are representative of larger land areas. During onshore flow temperatures at Sandy Way are strongly influenced by the Lake but the airport is influenced by the Lake to a lesser extent.

Heating or cooling of the air in the lower range gates of the RASS (due to differences in upwind surfaces or advection) has the potential to differ from processes over the Lake. During late morning through afternoon, with onshore flows (driven by surface heating of the land) some excess heating of the air in the lower range gates over SLT Airport is expected as compared to conditions over the Lake. These conditions could cause some under estimation of mixing depth over the Lake during daytime hours. Conversely, during night and early morning hours drainage flows over the airport will likely cool air in the lower range gates compared to temperatures at the same altitudes over the Lake. Under these conditions comparison of the RASS observations with surface temperatures measured at land sites near the Lake shore should provide reasonable estimates of mixing depth. However, use of RASS observations of temperature obtained during drainage flows to represent temperatures over the Lake during those same periods are expected to result in overestimates of the maximum mixing depth on the Lake. An alternative analysis might include compensation for the expected biases in aloft temperature observed over SLTahoe Airport as compared to temperatures expected aloft over the Lake.

Tables 2-1 contrasts estimates of the potential maximum mixing over the Lake (based on observations at the TDR1 buoy and assumptions discussed above) and expected mixing over a land site near the shoreline (based on observations at Sandy Way). Estimates of the maximum mixing depth over the Lake are summarized in **Table 2-1a**. Seasonal frequency distributions of mixing to specified heights by time of day are provided in the column labeled "Freq". These estimates of mixing are based on a surface air temperature assumed to equal the larger of either the hourly air temperature or the hourly water temperature (adjusted to mimic skin temperature) at TDR1. This assumption maximizes the estimated mixing depth over the Lake and presumes that, for some location over the Lake, the air temperature is warmed to the water temperature observed at TDR1 buoy. The count is the number of simultaneous hourly temperature observations at the surface and the specified height. The counts generally decrease with height and thus estimates of the frequency of mixing at the upper levels are uncertain. Physical principles suggest that the percent frequency values should decrease or remain constant with increasing height. Instances in which the percent frequency values increase with height are indicative of uncertainty in RASS observations of virtual temperature.

The results suggest deep mixing is possible over the Lake during winter and spring. In spring the apparent variation in mixing depth from morning to mid day is probably an artifact of warming of the surface layer over the airport that is not occurring to nearly the same extent over the Lake. Mixing over the Lake, even the maximum mixing per this estimate presented here, is apparently limited during fall and especially during summer as compared to the mixing depths over the Lake in winter and spring.

The similarly constructed estimates of mixing over Sandy Way, summarized in **Table 2-1b** are easier to interpret. They are based upon the air temperature and humidity at the surface as observed at Sandy Way. The resulting estimates of mixing depth for Sandy Way are qualitatively quite different from those suggested over the Lake (**Table 2-1a**). Over land the night and early morning mixing depths are very low during all seasons and maximum mixing depths occur during mid day or afternoon. The estimated daytime mixing depths increase in height through the day as expected. During the summer, the depths of mixing over land exceed those predicted for over the Lake.

Table 2-1a. Seasonal frequency of an estimated maximum potential mixing depth over Lake Tahoe reaching specified heights is shown in column labeled "Freq". Count is the number of hourly data pairs utilized. See text for description of caveats, and assumptions. Shading indicates median of estimated mixing depth values.

Season: Winter

ELEV	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count
3480		0		0		0		0	0%	1		0
3420		0		0		0	0%	1	0%	2		0
3359		0		0		0	33%	3	0%	3	0%	1
3299	67%	3	100%	1	100%	1	50%	4	13%	8	100%	1
3240	71%	7	100%	2	100%	1	60%	5	20%	10	25%	4
3180	33%	6	100%	2	67%	3	64%	11	27%	11	57%	7
3119	63%	8	50%	4	25%	4	47%	15	36%	14	45%	11
3059	59%	27	33%	9	50%	8	63%	16	21%	19	39%	18
3000	46%	41	38%	13	50%	10	55%	22	34%	32	50%	22
2940	44%	50	50%	14	57%	14	48%	29	32%	37	47%	30
2880	43%	67	54%	24	50%	20	39%	36	43%	42	50%	30
2819	45%	78	33%	30	62%	29	48%	46	41%	54	50%	42
2759	42%	104	48%	46	56%	32	54%	57	49%	71	53%	51
2700	53%	118	59%	54	63%	41	61%	74	50%	80	51%	57
2640	60%	124	63%	59	77%	44	66%	90	53%	93	63%	63
2579	62%	144	66%	61	69%	52	71%	95	61%	99	63%	65
2519	68%	156	69%	61	71%	59	71%	99	60%	108	63%	70
2460	67%	163	73%	64	74%	70	71%	101	61%	109	70%	74
2400	72%	179	80%	75	75%	76	76%	107	62%	117	69%	74
2339	76%	188	85%	82	83%	75	78%	116	73%	120	79%	81
2279	84%	205	86%	83	84%	80	83%	120	78%	116	87%	79
2220	89%	210	91%	81	85%	86	84%	120	80%	114	86%	88
2160	93%	221	96%	83	87%	85	87%	123	82%	119	92%	85
2099	97%	221	99%	70	91%	86	90%	128	86%	127	98%	86
2039	99%	206	99%	69	90%	82	91%	127	87%	126	99%	86
1980	99%	186	100%	55	91%	75	91%	115	93%	120	100%	84
Winter 200	0000-0659		0700-0959		1000-1259		1300-1659		1700-2059		2100-2359	

Season: Spring

ELEV	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count
3480		0		0		0		0		0		0
3420		0		0		0		0	0%	3		0
3359		0		0		0		0	29%	7	0%	1
3299	100%	1		0		0		0	30%	10	0%	3
3240	33%	3		0		0	100%	1	50%	16	33%	6
3180	86%	7		0		0	100%	1	47%	19	50%	8
3119	80%	10	100%	1		0	33%	3	50%	18	53%	15
3059	70%	23	83%	6	40%	5	0%	3	44%	25	50%	26
3000	63%	32	91%	11	50%	10	25%	8	50%	32	38%	40
2940	59%	54	65%	23	57%	14	38%	13	47%	43	42%	38
2880	53%	70	59%	32	52%	23	57%	23	51%	53	38%	42
2819	54%	102	61%	44	51%	41	55%	33	52%	62	40%	50
2759	53%	129	62%	65	54%	46	43%	47	56%	90	37%	57
2700	49%	147	59%	71	45%	60	42%	59	57%	116	37%	71
2640	51%	179	65%	86	47%	75	51%	77	57%	127	40%	83
2579	51%	196	65%	102	51%	87	51%	91	56%	139	37%	87
2519	52%	213	65%	108	51%	93	51%	105	54%	155	39%	104
2460	51%	235	65%	111	56%	93	51%	111	52%	152	41%	113
2400	53%	253	65%	117	49%	100	53%	113	52%	155	38%	118
2339	55%	255	70%	120	58%	99	54%	114	57%	159	46%	121
2279	56%	264	73%	123	56%	99	55%	119	56%	161	45%	126
2220	58%	279	67%	128	56%	100	57%	129	57%	164	45%	128
2160	61%	268	68%	127	57%	115	59%	135	57%	159	45%	130
2099	64%	269	71%	133	66%	116	62%	127	56%	154	54%	139
2039	70%	260	74%	130	72%	108	62%	125	61%	157	62%	134
1980	81%	213	81%	111	74%	88	62%	104	63%	135	65%	118
Spring 200	0000-0659		0700-0959		1000-1259		1300-1659		1700-2059		2100-2359	

Table 2-1a (continued). Seasonal frequency of an estimated maximum potential mixing depth over Lake Tahoe.

Season: Summer

ELEV	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count
3480		0		0		0		0		0		0
3420	0%	1		0		0		0	0%	1	0%	1
3359	0%	2		0		0		0	0%	1	0%	2
3299	0%	3		0		0		0	0%	2	0%	4
3240	0%	6		0		0		0	0%	3	0%	4
3180	0%	8		0		0		0	0%	4	0%	8
3119	0%	12		0		0		0	0%	5	0%	11
3059	0%	17	0%	1	0%	1	0%	1	0%	5	0%	10
3000	0%	21	0%	4	0%	1	0%	1	0%	7	0%	13
2940	0%	28	0%	5	0%	2	0%	2	0%	15	0%	17
2880	0%	32	0%	9	0%	4	17%	6	0%	19	5%	19
2819	0%	42	0%	13	0%	5	14%	7	3%	31	4%	28
2759	0%	49	6%	17	0%	7	10%	10	3%	35	0%	30
2700	0%	57	6%	16	0%	12	10%	10	2%	41	0%	37
2640	1%	67	5%	21	5%	19	9%	11	7%	41	2%	44
2579	1%	75	6%	33	5%	20	13%	15	9%	45	10%	41
2519	2%	101	12%	41	5%	22	25%	16	11%	47	6%	48
2460	5%	91	7%	41	17%	24	13%	16	7%	56	15%	52
2400	6%	98	11%	44	19%	26	26%	19	6%	53	11%	55
2339	14%	102	18%	56	41%	22	40%	15	13%	54	18%	56
2279	18%	107	26%	61	48%	23	64%	22	18%	51	19%	58
2220	18%	105	33%	64	50%	32	64%	22	20%	54	23%	62
2160	25%	114	50%	64	67%	39	79%	19	34%	56	29%	65
2099	43%	123	68%	62	86%	43	94%	17	69%	55	55%	69
2039	55%	128	74%	58	91%	45	96%	25	83%	54	69%	68
1980	93%	76	79%	33	83%	24	93%	15	87%	39	82%	38
ummer 200	0000-0659		0700-0959		1000-1259		1300-1659		1700-2059		2100-2359	

Season: Fall

ELEV	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count
3480		0		0		0		0		0		0
3420		0		0		0		0	0%	2	0%	1
3359	0%	2		0		0		0	0%	2	0%	2
3299	0%	1		0		0		0	0%	5	0%	3
3240	0%	7	0%	1		0		0	0%	5	0%	3
3180	11%	9	0%	2	0%	1	0%	1	0%	9	0%	5
3119	8%	13	0%	5	0%	3	0%	3	0%	13	0%	7
3059	0%	20	0%	7	0%	4	0%	6	0%	16	0%	7
3000	0%	28	18%	11	27%	11	0%	10	0%	24	0%	12
2940	4%	45	20%	15	27%	11	20%	15	8%	36	5%	20
2880	10%	59	17%	23	23%	13	24%	25	10%	42	11%	36
2819	15%	72	23%	35	38%	26	21%	34	13%	55	20%	45
2759	20%	98	22%	45	31%	36	21%	47	16%	63	16%	57
2700	23%	137	26%	58	35%	52	35%	66	21%	89	19%	67
2640	33%	158	42%	71	39%	66	36%	83	36%	111	37%	78
2579	38%	185	42%	76	48%	80	45%	96	37%	121	36%	95
2519	42%	234	49%	91	52%	96	42%	119	39%	136	34%	110
2460	50%	260	48%	95	56%	107	48%	130	42%	151	38%	115
2400	50%	271	50%	111	53%	118	48%	145	43%	155	41%	112
2339	59%	279	62%	117	57%	122	51%	153	48%	168	53%	118
2279	64%	291	66%	119	61%	129	49%	154	51%	179	53%	123
2220	65%	295	71%	118	61%	127	47%	149	48%	156	59%	126
2160	67%	297	68%	126	63%	126	52%	161	57%	179	61%	117
2099	74%	297	72%	127	65%	124	51%	157	64%	171	73%	122
2039	81%	302	78%	120	63%	128	55%	158	69%	179	77%	124
1980	94%	267	83%	110	66%	120	53%	140	76%	156	87%	110
Fall 2003	0000-0659		0700-0959		1000-1259		1300-1659		1700-2059		2100-2359	

Table 2-2b. Seasonal frequency of estimated mixing through specified depths over Sandy Way.

Season: Winter

ELEV	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count
3480		0		0		0		0	0%	1		0
3420		0		0		0	0%	1	0%	2		0
3359		0		0		0	0%	3	0%	3	0%	1
3299	0%	3	0%	1	0%	1	0%	4	0%	8	0%	1
3240	0%	9	0%	2	0%	1	0%	5	0%	10	0%	5
3180	0%	10	0%	2	0%	3	9%	11	0%	13	0%	9
3119	0%	14	0%	4	0%	4	0%	15	6%	17	0%	12
3059	0%	34	0%	9	13%	8	6%	16	0%	24	0%	22
3000	0%	49	0%	13	0%	10	0%	22	3%	39	0%	28
2940	0%	61	0%	14	13%	15	14%	29	2%	47	0%	37
2880	0%	76	0%	24	9%	22	8%	36	2%	51	0%	38
2819	0%	93	3%	30	10%	30	9%	47	2%	66	0%	54
2759	0%	121	4%	47	12%	33	12%	58	1%	85	0%	65
2700	0%	140	6%	54	12%	43	12%	77	1%	95	0%	73
2640	1%	149	10%	60	21%	47	18%	97	1%	110	0%	79
2579	0%	168	9%	65	23%	57	17%	104	1%	116	0%	82
2519	1%	186	15%	66	26%	69	16%	110	2%	128	0%	87
2460	2%	198	13%	68	27%	79	16%	114	2%	128	0%	91
2400	0%	217	13%	80	20%	86	17%	121	1%	137	0%	91
2339	0%	225	22%	85	31%	84	22%	131	1%	143	0%	99
2279	1%	244	20%	89	33%	88	23%	136	2%	137	0%	96
2220	2%	250	21%	86	36%	96	26%	134	3%	135	3%	104
2160	2%	263	27%	88	33%	92	28%	137	3%	143	4%	102
2099	4%	259	38%	74	53%	91	40%	141	9%	150	6%	105
2039	6%	241	42%	74	60%	89	40%	141	12%	146	7%	106
1980	8%	222	57%	61	71%	83	46%	128	13%	135	10%	99
Winter 200	0000-0659		0700-0959		1000-1259		1300-1659		1700-2059		2100-2359	

Season: Spring

ELEV	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count
3480		0		0		0		0		0		0
3420		0		0		0		0	0%	6	0%	1
3359		0		0		0		0	11%	9	0%	2
3299	0%	1	0%	1		0		0	8%	12	0%	5
3240	0%	3	0%	2		0	100%	1	5%	19	0%	7
3180	0%	8	0%	2		0	100%	1	17%	24	0%	10
3119	0%	16	0%	4	0%	1	33%	3	13%	23	0%	19
3059	0%	35	20%	10	14%	7	0%	4	13%	30	0%	32
3000	0%	48	27%	15	14%	14	11%	9	10%	41	0%	48
2940	0%	71	41%	27	21%	19	35%	17	13%	55	0%	49
2880	0%	92	25%	36	21%	28	45%	29	16%	70	0%	53
2819	0%	129	24%	49	33%	48	47%	43	13%	80	0%	66
2759	1%	161	27%	74	37%	54	44%	57	16%	110	1%	77
2700	1%	184	31%	83	45%	73	48%	73	16%	141	3%	100
2640	2%	231	42%	103	45%	92	56%	94	20%	157	5%	114
2579	1%	257	40%	121	46%	111	53%	108	18%	176	4%	119
2519	2%	272	42%	130	48%	118	53%	123	18%	194	5%	133
2460	2%	292	46%	134	52%	120	53%	129	20%	194	3%	146
2400	2%	316	43%	146	50%	127	53%	132	18%	198	5%	151
2339	4%	324	55%	148	63%	126	56%	134	26%	200	6%	151
2279	4%	332	58%	151	65%	126	58%	139	26%	202	4%	157
2220	5%	349	59%	154	62%	127	58%	150	26%	210	8%	159
2160	5%	336	58%	150	66%	142	57%	158	26%	206	9%	170
2099	8%	330	70%	157	79%	140	68%	145	32%	206	16%	175
2039	10%	319	75%	150	82%	132	68%	141	33%	200	18%	171
1980	14%	251	88%	128	82%	105	70%	115	36%	167	23%	141
Spring 200	0000-0659		0700-0959		1000-1259		1300-1659		1700-2059		2100-2359	

Table 2-1b (continued). Seasonal frequency of estimated mixing through specified depths over Sandy Way.

Season: Summer

ELEV	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count
3480		0		0		0		0		0		0
3420	0%	1		0		0		0	0%	1	0%	1
3359	0%	2		0		0		0	0%	1	0%	2
3299	0%	3		0		0		0	0%	2	0%	4
3240	0%	6		0		0		0	0%	3	0%	4
3180	0%	8		0		0		0	0%	4	0%	8
3119	0%	12		0		0		0	0%	5	0%	11
3059	0%	17	0%	1	0%	1	100%	1	0%	5	0%	10
3000	0%	21	25%	4	0%	1	100%	1	0%	7	0%	13
2940	0%	28	20%	5	0%	2	100%	2	0%	15	0%	17
2880	0%	32	44%	9	0%	4	83%	6	0%	19	0%	19
2819	0%	42	38%	13	0%	5	71%	7	10%	31	0%	28
2759	0%	49	41%	17	29%	7	70%	10	11%	35	0%	30
2700	0%	57	38%	16	27%	11	80%	10	10%	41	0%	37
2640	0%	67	38%	21	50%	18	100%	11	12%	41	0%	44
2579	0%	75	36%	33	63%	19	93%	15	16%	45	0%	41
2519	0%	101	32%	41	62%	21	94%	16	15%	47	0%	48
2460	0%	91	29%	41	74%	23	87%	15	14%	56	0%	52
2400	0%	98	36%	44	80%	25	83%	18	13%	53	0%	55
2339	0%	102	49%	55	86%	21	93%	14	19%	54	0%	56
2279	2%	107	56%	61	91%	22	95%	21	22%	51	0%	58
2220	2%	105	62%	63	97%	31	95%	21	22%	54	0%	62
2160	2%	114	70%	64	97%	38	100%	18	29%	56	0%	65
2099	5%	123	84%	62	100%	42	100%	17	44%	55	6%	69
2039	8%	128	90%	58	100%	44	100%	25	52%	54	7%	68
1980	18%	76	94%	33	100%	23	93%	15	62%	39	5%	38
ummer 200	0000-0659		0700-0959		1000-1259		1300-1659		1700-2059		2100-2359	

Season: Fall

ELEV	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count	Freq	Count
3480		0		0		0		0		0		0
3420		0		0		0		0	0%	2	0%	1
3359	0%	2		0		0		0	0%	2	0%	2
3299	0%	1		0		0		0	0%	5	0%	3
3240	0%	8	0%	1		0		0	0%	5	0%	3
3180	0%	10	0%	2	0%	1	0%	1	0%	9	0%	5
3119	0%	17	0%	7	0%	3	0%	3	0%	13	0%	7
3059	0%	26	0%	9	0%	4	0%	6	0%	16	0%	7
3000	0%	36	0%	13	0%	12	0%	10	0%	24	0%	12
2940	0%	51	12%	17	27%	11	7%	15	0%	36	0%	21
2880	0%	67	4%	25	27%	15	8%	25	0%	42	0%	38
2819	0%	84	5%	38	24%	29	11%	35	0%	56	0%	47
2759	0%	112	6%	49	18%	40	8%	48	0%	66	0%	59
2700	0%	152	6%	63	25%	57	9%	69	0%	95	0%	71
2640	0%	178	14%	78	38%	73	17%	88	1%	119	0%	81
2579	0%	207	20%	83	40%	87	17%	103	1%	131	1%	100
2519	0%	253	24%	98	40%	104	21%	127	1%	149	1%	117
2460	0%	278	26%	101	43%	115	19%	140	3%	163	2%	122
2400	0%	289	24%	118	41%	126	17%	153	2%	167	3%	117
2339	0%	298	32%	125	53%	130	22%	162	2%	179	3%	126
2279	1%	308	33%	129	54%	138	24%	164	4%	189	3%	129
2220	2%	310	35%	129	54%	134	22%	158	4%	162	5%	133
2160	2%	317	40%	136	51%	134	27%	172	4%	189	5%	122
2099	3%	317	53%	135	60%	131	35%	166	8%	180	9%	127
2039	5%	318	54%	128	63%	136	38%	167	13%	189	8%	130
1980	6%	283	67%	118	64%	128	32%	148	13%	166	15%	117
Fall 2003	0000-0659		0700-0959		1000-1259		1300-1659		1700-2059		2100-2359	

2.3 Wind Patterns

Winds are of interest when addressing atmospheric deposition because they can move emissions of pollutants from one area to another and the associated turbulence can affect the rates of deposition.

2.3.1 Surface Winds

2.3.1.1 Outside the Tahoe Basin

Winds in northern California tend to have a westerly (west to east) component due to its mid-latitude location in the northern hemisphere where westerly winds dominate the global circulation patterns. This typical pattern is perturbed near ground level however by the presence of mountain ranges (Coastal Ranges and Sierra Nevada) separated by the Great Central Valley of California. Furthermore, the valleys and mountain slopes create strong diurnal mesoscale variations in the global wind pattern. The diurnal and seasonal variations in wind speed and direction are graphically summarized for the Blue Canyon Airport in **Figure 2-23**. Blue Canyon is at an approximate elevation of 5200 feet MSL (about 1000 feet lower than Lake Tahoe). Several wind features typical of mountain settings can be seen in the figure. First, average wind speeds are greatest about mid-day and tend to be stronger in summer than in other seasons. Second, the winds tend to have a westerly component during the day and an easterly component during the night. This pattern is consistent with up-slope air flow during the day and down-slope or drainage flows during the night. As the sun warms the western slopes of the Sierra, the air tends to rise and flow eastward. After the sun sets, the surface layer of air cools and flows downhill.

Closer to the crest of the Sierra Nevada, readily available meteorological data for Donner Summit (NW of Lake Tahoe) in the Sierra Nevada are summarized in **Tables 2-2 and 2-3**. At Donner Summit, the two predominant wind directions are WSW and ENE. The westerly-enhanced up-slope flows occur primarily during the day and slower, down-slope ENE flows occur primarily during the night. The up-slope flows occur during about 2/3rds of the time and down-slope flows occur about 25% of the time. Thus, calm winds and wind directions other than WSW or ENE are relatively rare. Resultant winds, shown in **Table 2-3**, represent the net movement of air. The net movement is from the SW in all seasons and is strongest and most persistent during winter and summer. Presented in **Figure 2-24** are seasonal wind roses for Donner Summit that demonstrate the upslope/downslope wind pattern is present in all seasons with relatively minor variations. It is likely that channeling of the winds through the pass may enhance the consistency of wind directions at this location.

Further east and at a higher altitude, winds are also measured near the peak of Slide Mountain in Nevada. Slide Mountain is located NNE of Lake Tahoe at an elevation of 9,650 feet MSL. This elevation is typically about 1000 feet below the subsidence inversion associated with the eastern Pacific high pressure system. A wind rose is presented for Slide Mountain in **Figure 2-25**. The predominant wind directions are similar to those at Donner Summit, although the flows are less channeled, and are probably the best land-based measurements of the free air flow over the Sierra Nevada. Winds have a southwesterly component (i.e., transport potential from the Sacramento metropolitan region) over 40 percent of the time. The annual average wind speed is 18.7 mph at this elevation (**Figure 2-26**), considerably higher than surface wind speeds at lower altitude sites. Peak wind speeds are over 100 mph.

Table 2-2. Summary of Predominant Winds at Donner Summit. (CARB, 1984)

Statistic \ Season:	Winter	Spring	Summer	Fall	Annual
Primary Direction					
Direction	WSW	WSW	WSW	WSW	WSW
Mean Speed (mph)	20.0	16.0	12.6	15.9	16.2
Frequency (%)	69.3	63.2	70.3	63.7	66.6
Secondary Direction					
Direction	ENE	ENE	ENE	ENE	ENE
Mean Speed (mph)	13.6	11.5	8.0	11.0	11.3
Frequency (%)	26.8	28.1	19.6	29.9	26.2

Table 2-3. Resultant Winds at Donner Summit. (CARB, 1984)

Statistic \ Season:	Winter	Spring	Summer	Fall	Annual
Direction (degrees)$^{+}$	241	241	236	242	240
Speed (mph)	10.1	6.9	7.4	6.8	7.8
Persistance*	0.57	0.50	0.67	0.49	0.55

$^{+}$ Compass degrees (0 or 360 indicates wind from North, 90 indicates wind from East, 180 indicates wind from South, and 270 indicates wind from West)

* Ratio of resultant wind speed to mean wind speed (values can vary between 0 to 1 with "1" indicating that the wind is always from the resultant wind direction)

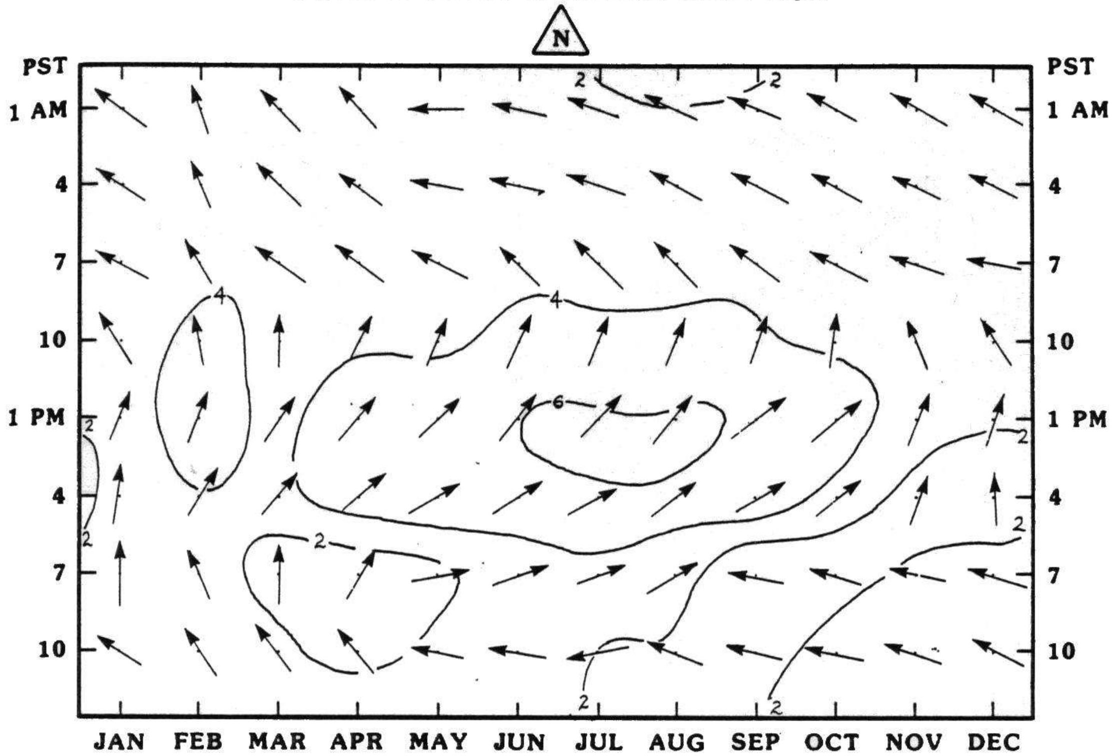
Figure 2-23. Diurnal and Seasonal Variations in Wind Patterns at Blue Canyon. (CARB, 1984)

BLUE CANYON (Blue Canyon Airport)

LATITUDE: 39° 17' N **LONGITUDE:** 120° 42' W

PERIOD: December 1974 - November 1979 **LEVEL:** Surface

MONTHLY THREE HOURLY RESULTANT WIND DIAGRAM
Direction (shown by arrows), Speed (mph)



SEASONAL THREE HOURLY, DAILY AND YEARLY RESULTANT WIND SUMMARY

	WINTER (Dec, Jan, Feb)		SPRING (Mar, Apr, May)		SUMMER (Jun, Jul, Aug)		FALL (Sep, Oct, Nov)		ANNUAL	
Time (PST)	Direction (deg)	Speed (mph)	Direction (deg)	Speed (mph)	Direction (deg)	Speed (mph)	Direction (deg)	Speed (mph)	Direction (deg)	Speed (mph)
1 AM	140	2.6	125	2.4	105	2.2	118	2.3	123	2.3
4 AM	135	2.6	121	2.7	107	2.3	118	2.2	121	2.4
7 AM	126	2.7	130	3.0	138	2.9	118	2.5	128	2.8
10 AM	159	3.3	191	3.6	200	5.1	183	3.6	185	3.8
1 PM	202	3.4	222	4.4	222	6.1	220	4.3	218	4.5
4 PM	198	2.3	229	4.3	236	5.4	228	3.2	227	3.7
7 PM	126	2.4	216	1.4	246	2.5	105	1.2	180	1.0
10 PM	130	2.7	128	2.1	098	2.0	110	2.3	117	2.2
DAILY	149	2.4	180	2.3	196	2.3	161	1.8	172	2.1

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Figure 2-24. Seasonal Wind Roses for Donner Summit. (based on CARB, 1984)

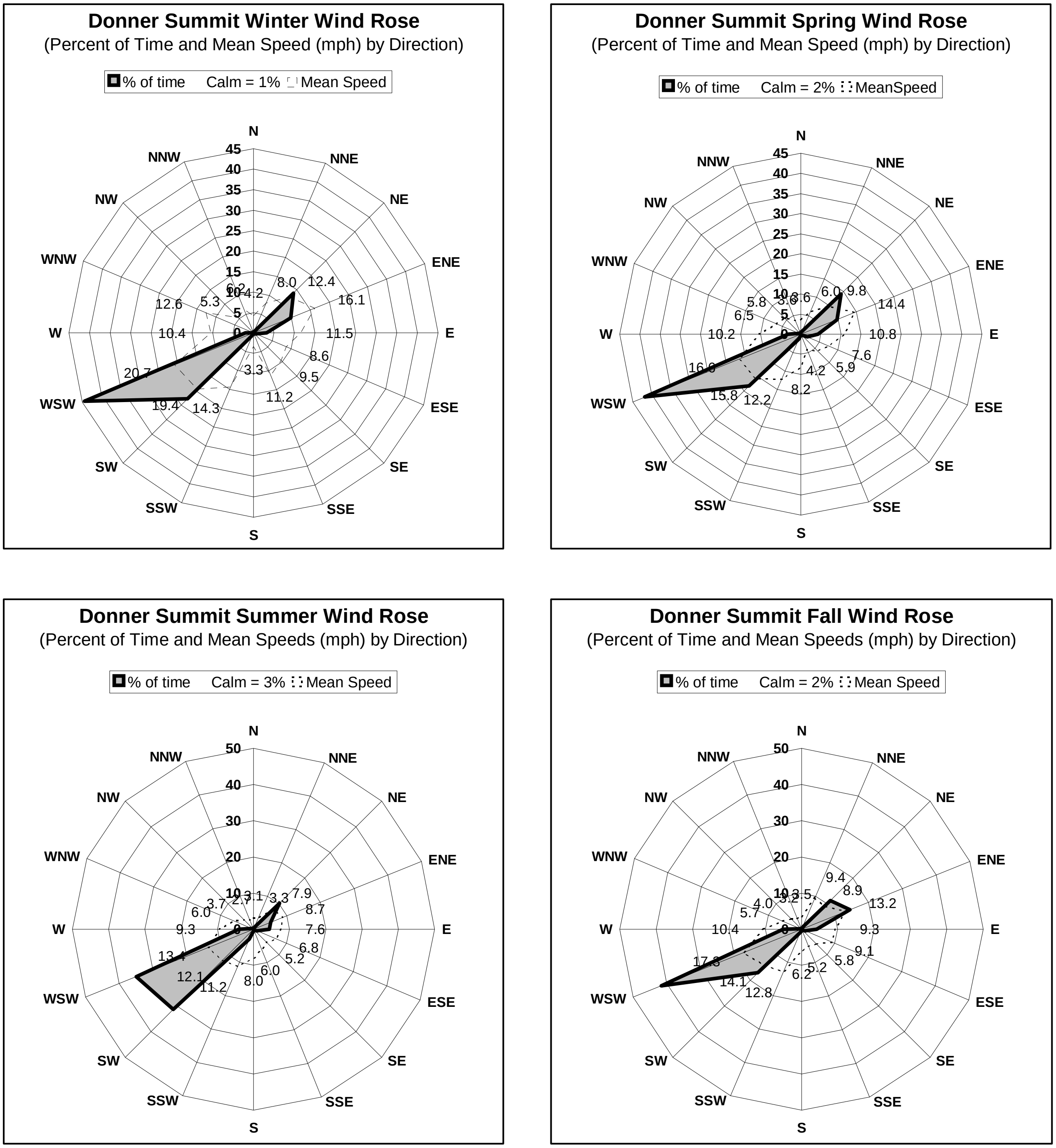


Figure 2-25. Wind Rose for Slide Mountain, NV based on 1968-1970 data. (WRCC, 2004)

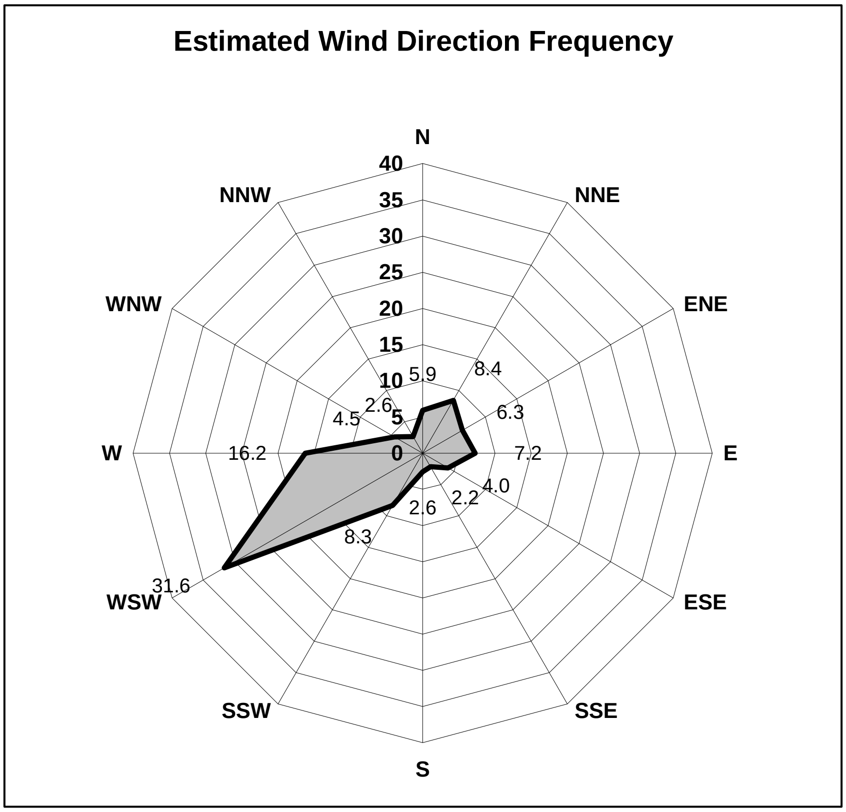
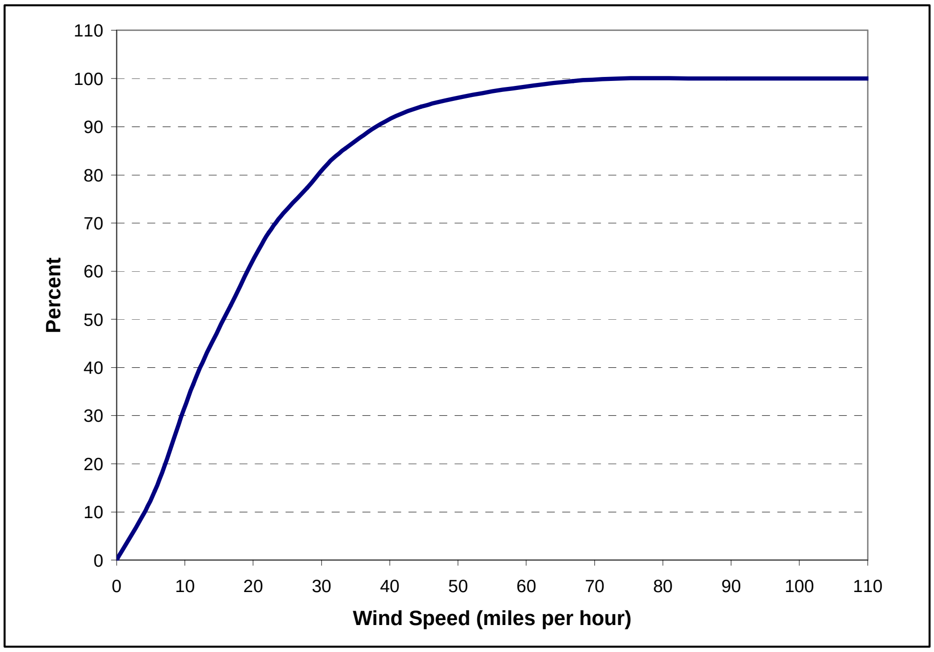


Figure 2-26. Cumulative Wind Speed Frequency for Slide Mountain, NV based on 1968-1970 data. (WRCC, 2004)



2.3.1.2 Inside the Tahoe Basin

In the Tahoe Basin itself, mesoscale weather strongly influences local air flow patterns. Resultant and predominant wind data are readily available for South Lake Tahoe (**Tables 2-4 and 2-5**) and are presented by season. Winds tend to be channeled at this site (airport) and are generally from the south or southwest. The resultant wind speeds are highest during summer (a factor of two greater than the spring or fall resultant speeds). The resultant wind speed in winter is enhanced by the routine passage of storm systems.

Table 2-4. Resultant Wind Data Summary for South Lake Tahoe. (CARB, 1984)

Statistic \ Season:	Winter	Spring	Summer	Fall	Annual
Direction (degrees)$^{+}$	187	225	215	213	208
Speed (mph)	3.8	2.1	4.5	2.1	3.0
Persistance*	0.52	0.26	0.53	0.31	0.39

$^{+}$ Compass degrees (0 or 360 indicates wind from North, 90 indicates wind from East, 180 indicates wind from South, and 270 indicates wind from West)

* Ratio of resultant wind speed to mean wind speed (values can vary between 0 to 1 with "1" indicating that the wind is always from the resultant wind direction)

Table 2-5. Predominant Wind Data Summary for South Lake Tahoe. (CARB, 1984)

Statistic \ Season:	Winter	Spring	Summer	Fall	Annual
Primary Direction					
Direction	S	SSW	SSW	S	SSW
Mean Speed (mph)	11.9	12.1	11.9	10.2	12.0
Frequency (%)	41.7	32.0	43.6	29.1	35.2
Secondary Direction					
Direction	NNE	N	N	N	N
Mean Speed (mph)	8.1	9.4	9.0	8.1	8.8
Frequency (%)	15.6	25.7	17.2	20.0	19.5

Wind roses (showing the directional frequency of surface winds) for the South Lake Tahoe Airport are presented by season in **Figure 2-27**. The bi-directional nature of the surface wind is of immediate note and is associated with down-slope drainage flows of cold air at night and up-slope flows during the day. The percentage of time with calm winds is significantly higher at the SLT-Airport than at other mountain sites shown earlier. Similarly, in the aloft wind measurements described in the following paragraphs, a higher frequency of calm winds was observed above the ground at SLT-Airport compared to over the western slope of the Sierra Nevada near the Grass Valley Radar Wind Profiler with Radio Acoustic Sounding System (RWP/RASS) site.

The mesoscale processes in the Tahoe Basin create a tendency for the winds to vary diurnally and to often be oriented perpendicular to the shoreline (i.e., up and down the mountain slopes). Thus, categorizing wind direction relative to the shoreline (onshore, offshore, or sideshore) can be more useful than compass wind direction when comparing the diurnal timing and orientation of the winds on different sides of the Lake. Seasonal bar charts of the proportion of each air flow type (i.e., calm, offshore, onshore, sideshore) by hour are provided for three sites representing different sectors of the Lake (South - SLT-Sandy Way, East – Cave Rock, and Northwest – USCG) in **Figures 2-28 through 2-31**. Downslope flow dominates during the night at all three sites and upslope flow dominates during most daylight hours. Obviously, downslope flows prevail during more hours in winter due to the longer nights and upslope flows are more prevalent in summer. When considering atmospheric deposition to the Lake, the periods of downslope air flows are likely to be a primary contributor to the temporal loading of the Lake. This pattern implies low-level convergence of air over the Lake at night and low-level divergence over the Lake during the day. Such a pattern suggests that local emissions would primarily contribute to deposition during the night and the potential for in-basin and out-of-basin emission sources to impact deposition during the day as air descends over the Lake to replace the low level air moving up the mountain slopes.

Figure 2-27. Seasonal wind roses for South Lake Tahoe. (based on CARB, 1984)

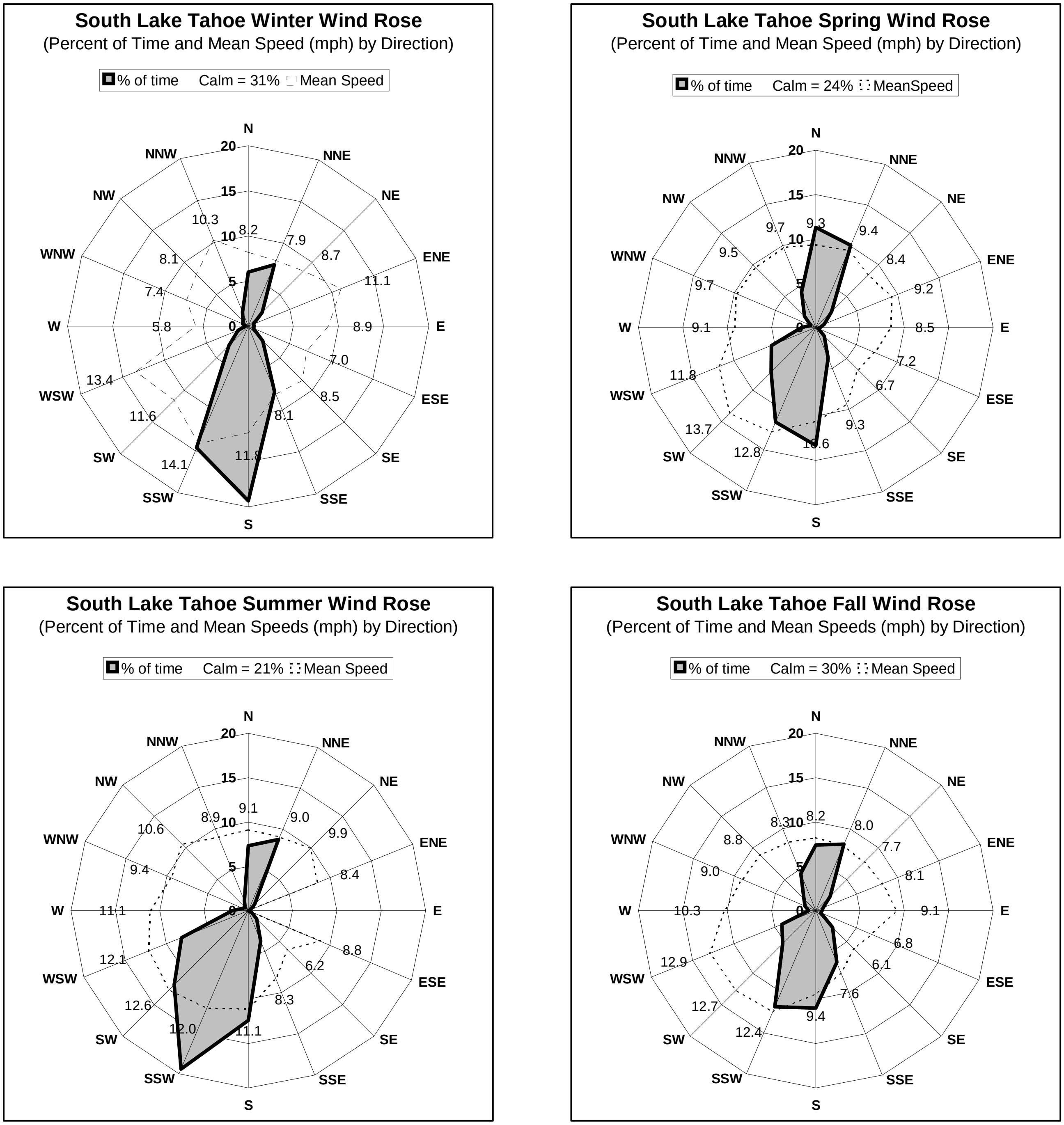


Figure 2-28. Winter Wind Patterns for SLT-Sandy Way (top), Cave Rock (middle), and Lake Forest - USCG (bottom) in 2003.

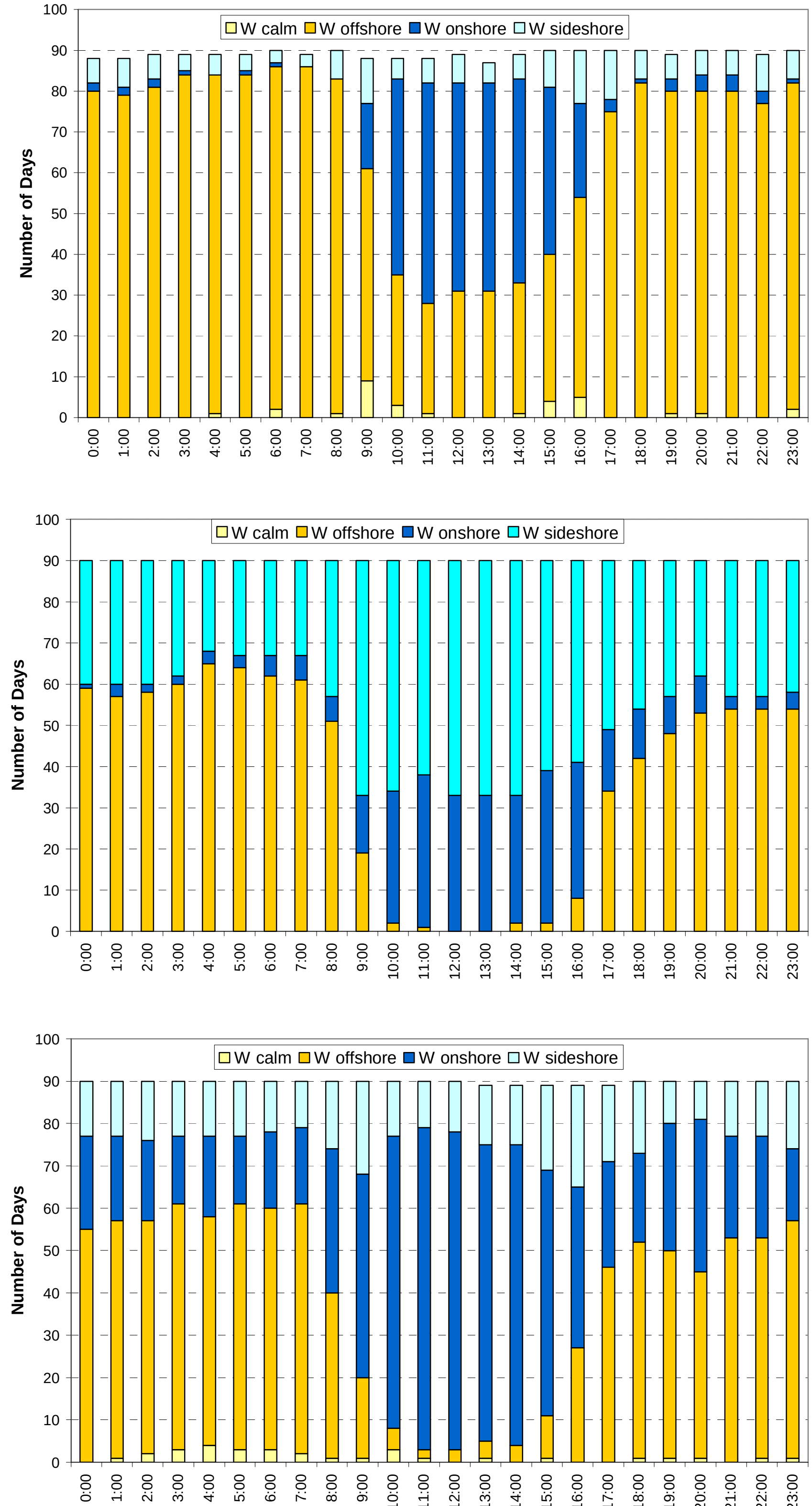


Figure 2-29. Spring Wind Patterns for SLT-Sandy Way (top), Cave Rock (middle), and Lake Forest - USCG (bottom) in 2003.

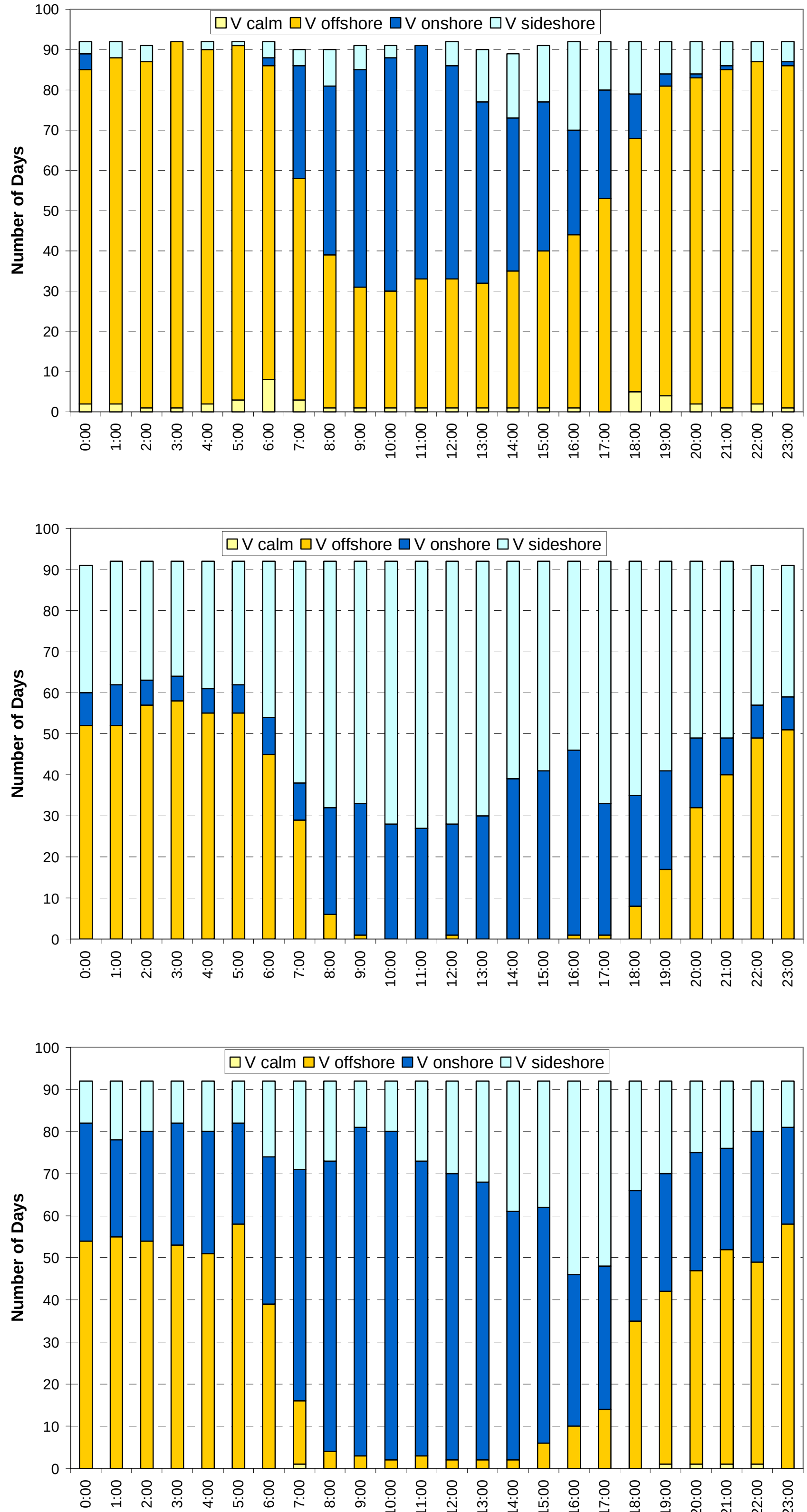


Figure 2-30. Summer Wind Patterns for SLT-Sandy Way (top), Cave Rock (middle), and Lake Forest - USCG (bottom) in 2003.

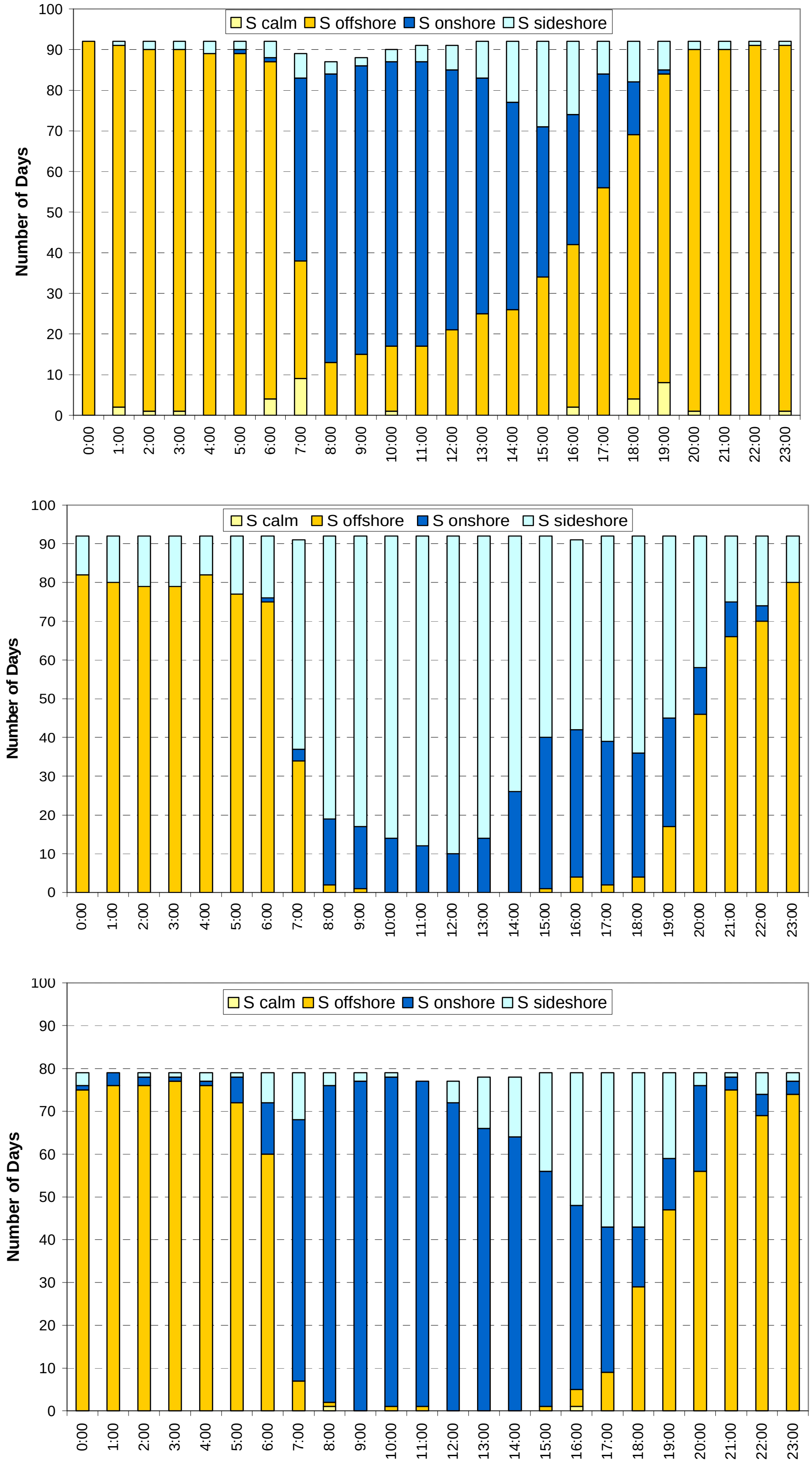
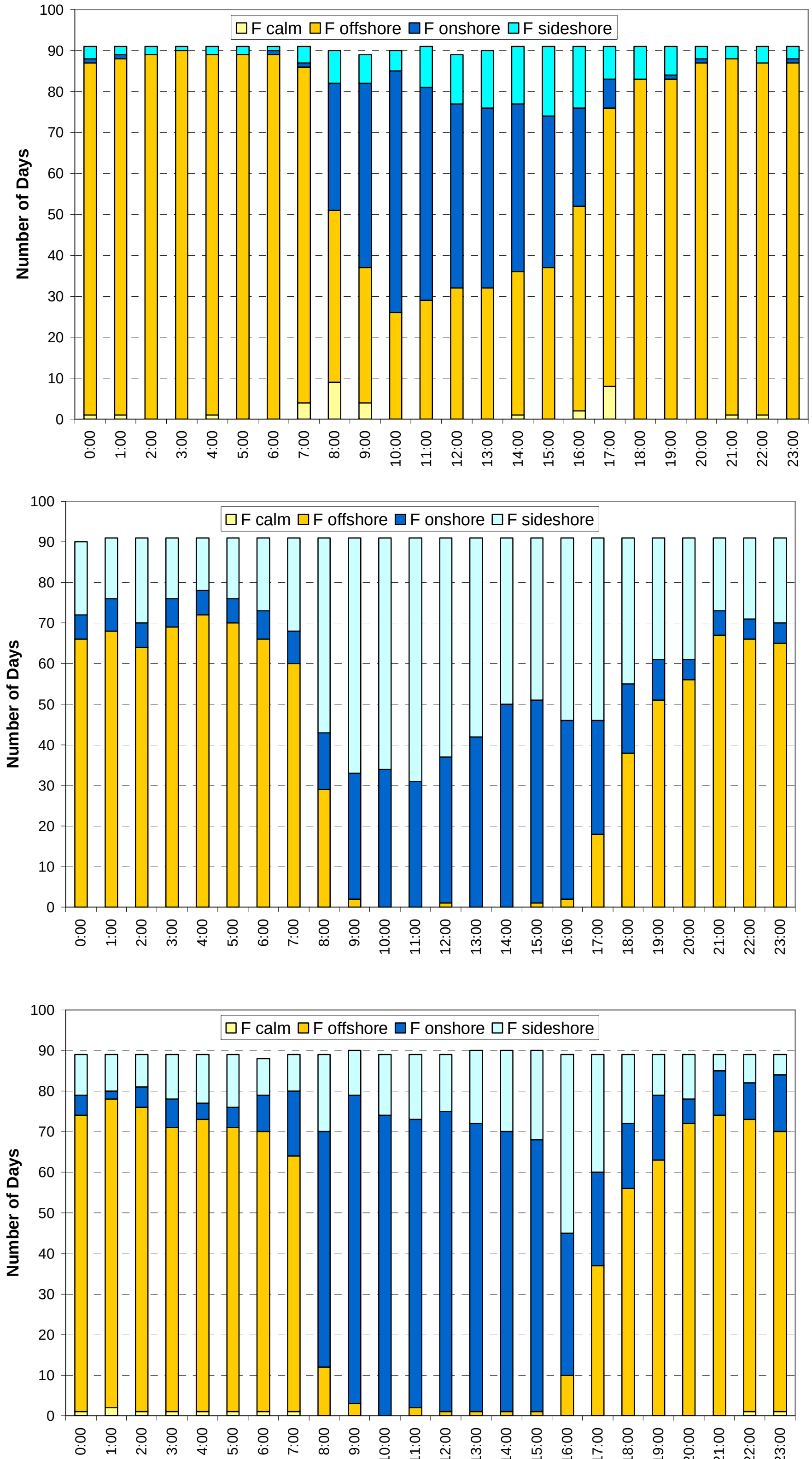


Figure 2-31. Fall Wind Patterns for SLT-Sandy Way (top), Cave Rock (middle), and Lake Forest - USCG (bottom) in 2003.



2.3.2 Winds Aloft

A limited number of balloon soundings and aircraft flights have been conducted where wind speeds and wind directions aloft have been measured. Twice-daily balloon soundings at Oakland, CA and Reno, NV provide the nearest long-term consistent observations of meteorological conditions aloft. Balloon soundings use to be conducted in Sacramento, CA to support daily decisions by the Air Resources Board regarding agricultural burning. A summary of the winds observed aloft during these soundings provide an indication of the potential frequency for transport of pollutants from the Central Valley to the Tahoe Basin. Seasonal summaries of the wind speeds and directions at 1000 and 3000 feet AGL are provided for 4 a.m., 10 a.m., and 4 p.m. PST in **Figures 2-32 and 2-33**. The seasonal frequencies of wind directions with the potential to transport material from the Central Valley to the Tahoe Basin are summarized in **Table 2-6**. These data show the greatest propensity for winds from the southwest through the west during the summer and the lowest propensity during the winter. Also, the frequency of winds from these “transport” directions is greater during the afternoon than during the morning. These data represent the maximum potential frequency for transport as they do not consider the wind speeds and persistence of the wind direction to effectively move material from the Valley to the Tahoe Basin. Furthermore, vertical mixing processes in the Valley, Sierra Nevada, and the Tahoe Basin would further act to reduce the impact of pollutant transport.

Table 2-6. Percent Frequency of Wind Directions above Sacramento with the potential* for transporting polluted air to the Tahoe Basin. (CARB, 1979)

Time (PST)	Winter	Spring	Summer	Fall	Annual
at 3000 feet above ground					
4 a.m.	13.6	28.6	38.5	28.2	29.1
10 a.m.	21.6	25.3	37.2	22.0	27.5
4 p.m.	19.4	46.2	70.2	39.1	45.1
at 1000 feet above ground					
4 a.m.	14.9	39.3	59.5	38.0	41.6
10 a.m.	18.3	37.4	63.6	25.8	39.3
4 p.m.	17.1	56.0	84.1	41.8	51.6

* wind direction from the west or southwest (i.e., between 195 and 285^{O}); for transport to occur, the temporal persistence of the wind speeds and directions must also be sufficient for the air mass to traverse the distance between Sacramento and the Sierra crest.

As seen from the annual summary graphs, Sacramento winds aloft are in the direction of the Tahoe Basin about 40% of the time during the morning and 50% of the time during the afternoon at the 1000 foot altitude and somewhat lower (30% and 45% of the time) at the 3000 foot altitude.

To provide better understanding of the winds above ground level, LTADS included radar wind profilers operated in the Tahoe Basin at the South Lake Tahoe Airport, elevation 1909 m (6263 feet) MSL, and on the western slope of the Sierra Nevada near Grass

Valley, elevation 689 m (2261 feet) MSL. As configured for LTADS, the radar wind profilers provided hourly averaged observations of wind speed and direction for vertical intervals (range gates) of about 60 meters. The lowest range gate provided the average winds between 90 and 150 m AGL. The maximum range varied with environmental conditions and was usually several kilometers AGL. Generally, rates of data recovery increase a little with height through the first few range gates and then decrease with height through the upper range gates.

The hourly LTADS wind observations observed above the South Lake Tahoe Airport were summarized by time of day and season. **Figure 2-34** is an example figure illustrating wind observations during summer as a time height cross section. Each of the small wind roses shows the mean speed and frequency of wind direction for a specific height and time interval. Each of the three lowest height intervals represents observations from two 60-meter range gates of the RASS. The fourth interval represents data from four range gates (~240 meters). The percent frequency of calms (defined in this figure as speed < 1 m/s) and the number of hours of observations available are noted for each time-height interval.

The dominant wind direction over South Lake Tahoe Airport is from the SW quadrant during all seasons for nearly all times of day and elevations. During daylight hours, a secondary direction from the N develops due to onshore, up-valley flow. The vertical extent and frequency of the N wind is greatest in summer and fall when it is evident as high as 2400 m MSL (about 500 m above lake-level). Even during winter when storms tend to occur and when the diurnal variation in temperature is least, the frequency of N winds remains higher during daylight hours than during the night. During winter, although the higher range gates detect northerly winds less frequently than during summer, it appears that the depth of up-valley flow over SLT-Airport may reach to 2400 m MSL during some days and hours.

Mini-SODARs were operated at three sites in the Tahoe Basin and one site on the western slope of the Sierra Nevada during LTADS. The mini-SODARs provide fine (5-meter) vertical resolution of wind speed and direction near the surface, providing vertical coverage that is complementary to the radar wind profilers. Their vertical range depends upon humidity conditions. During LTADS their range extended from near ground level into the first range gate of the radar wind profiler and did not consistently extend through the second range gate of the radar wind profiler.

The in-basin mini-SODAR sites were Tahoe City Wetlands, Incline Village General Improvement District, and the SLT Airport (collocated with the radar wind profiler). The western Sierra slope site was located at Big Hill, about 25 miles SW of Lake Tahoe at about the 6000’ MSL elevation. The hours of operation were restricted at Big Hill to limit noise near sleeping quarters for fire lookouts and fire fighters.

As an example of the observations obtained with the mini-SODAR, summer frequency distributions of wind speed and direction at SLT Airport are summarized in **Figure 2-35**. As in **Figure 2-34**, each wind rose represents the seasonal frequency distribution of wind speed and direction over a height interval during specified hours of the day.

Figure 2-32a. Seasonal Summary of 0400 PST Winds at 1000 Feet AGL at Sacramento Executive Airport. (based on CARB, 1979)

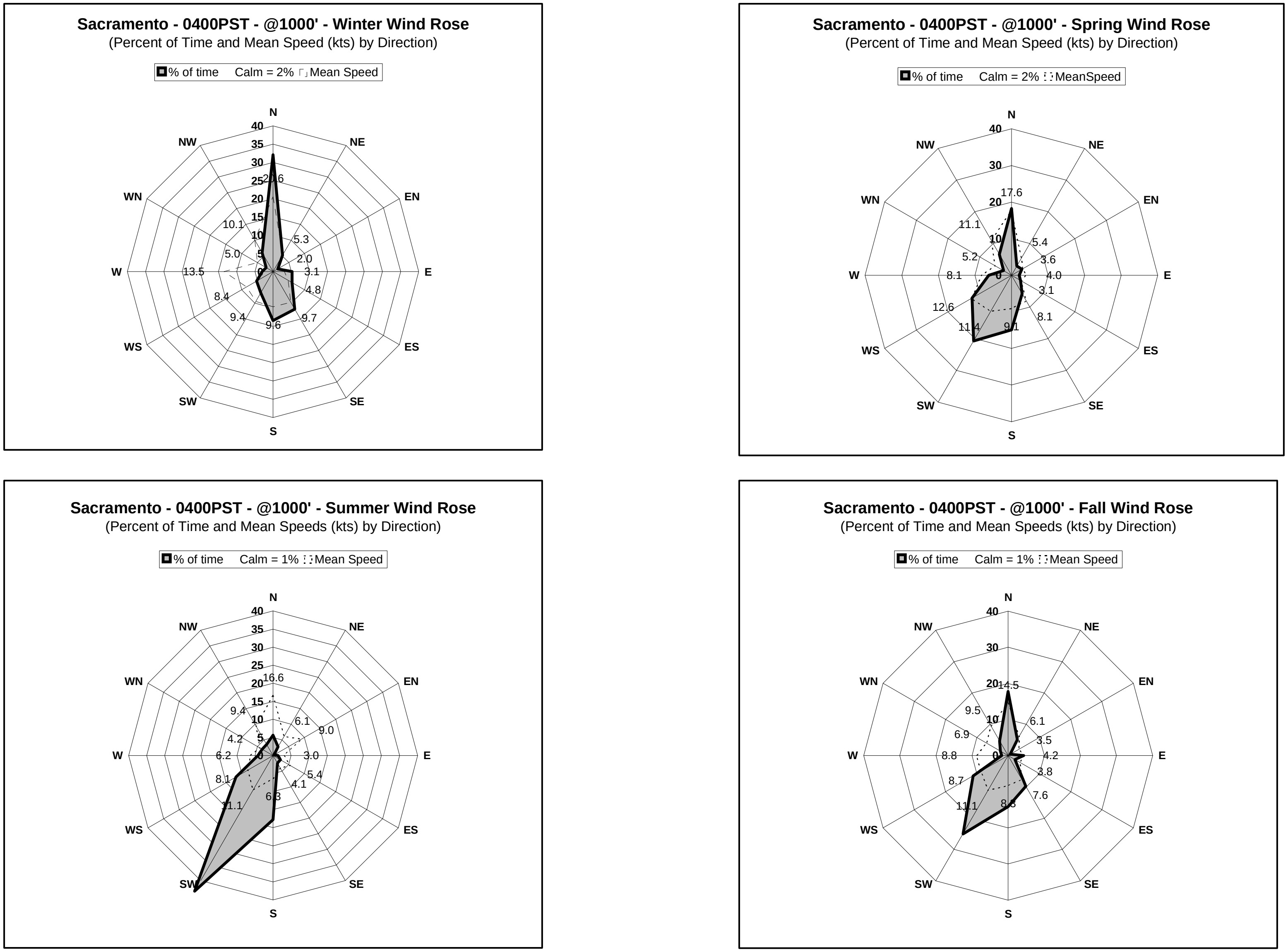
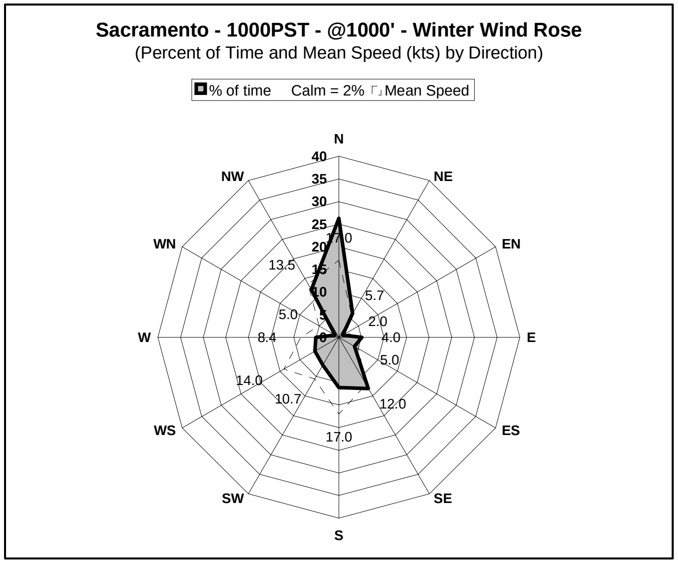
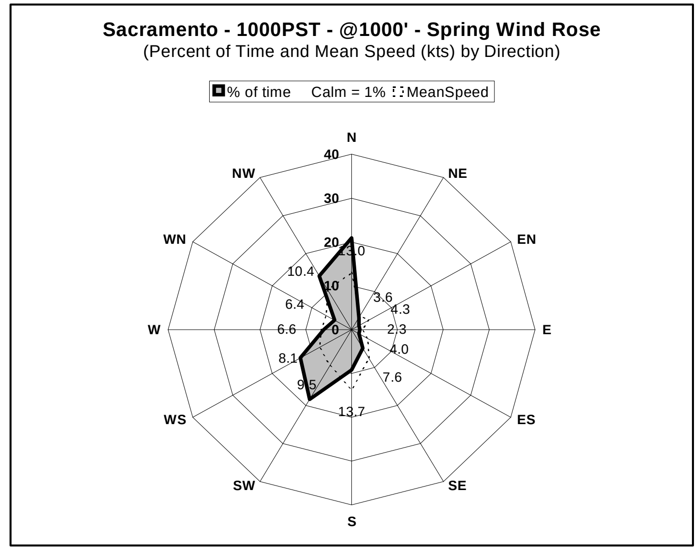
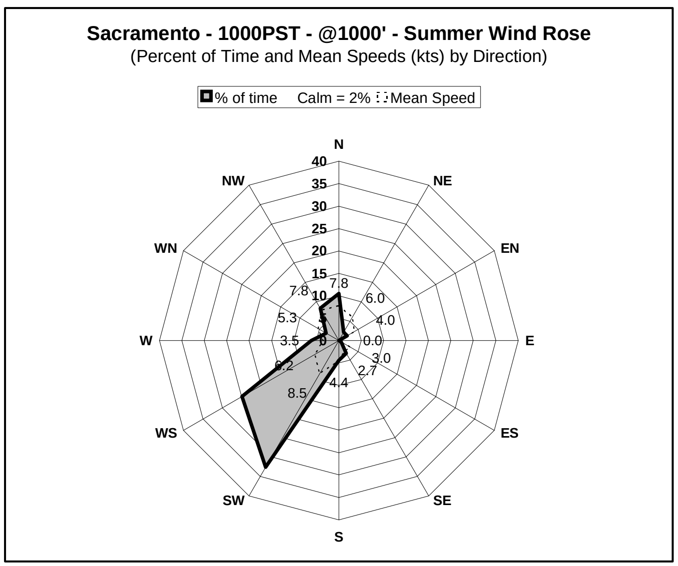


Figure 2-33b. Seasonal Summary of 1000 PST Winds at 1000 Feet AGL at Sacramento Executive Airport. (based on CARB, 1979)







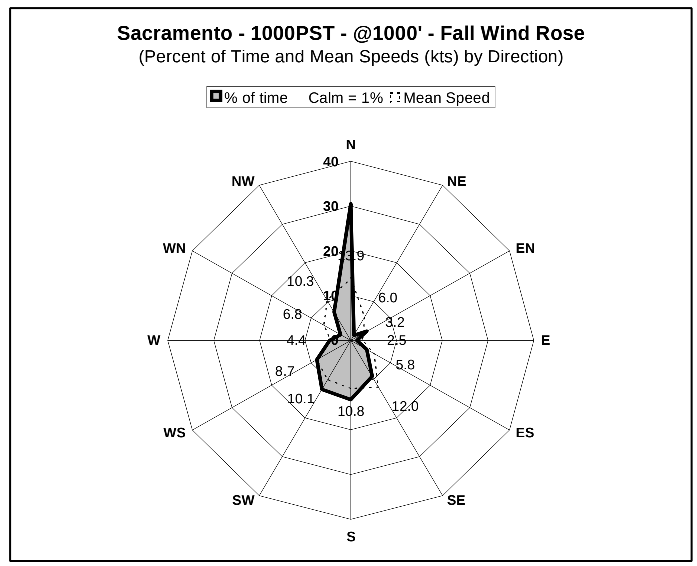


Figure 2-34c. Seasonal Summary of 1600 PST Winds at 1000 Feet AGL at Sacramento Executive Airport. (based on CARB, 1979)

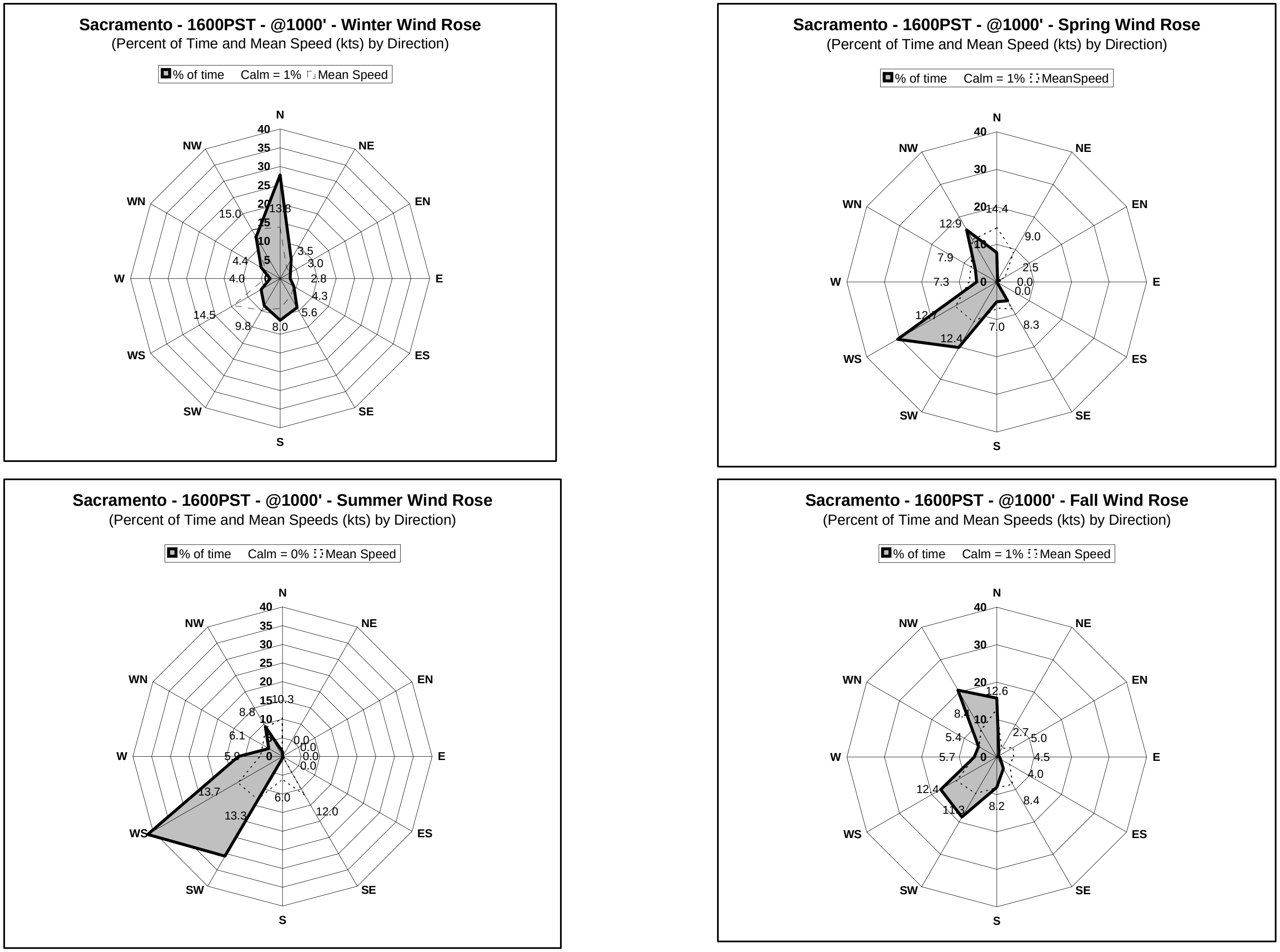


Figure 2-35a. Seasonal Summary of 0400 PST Winds at 3000 Feet AGL at Sacramento Executive Airport. (based on CARB, 1979)

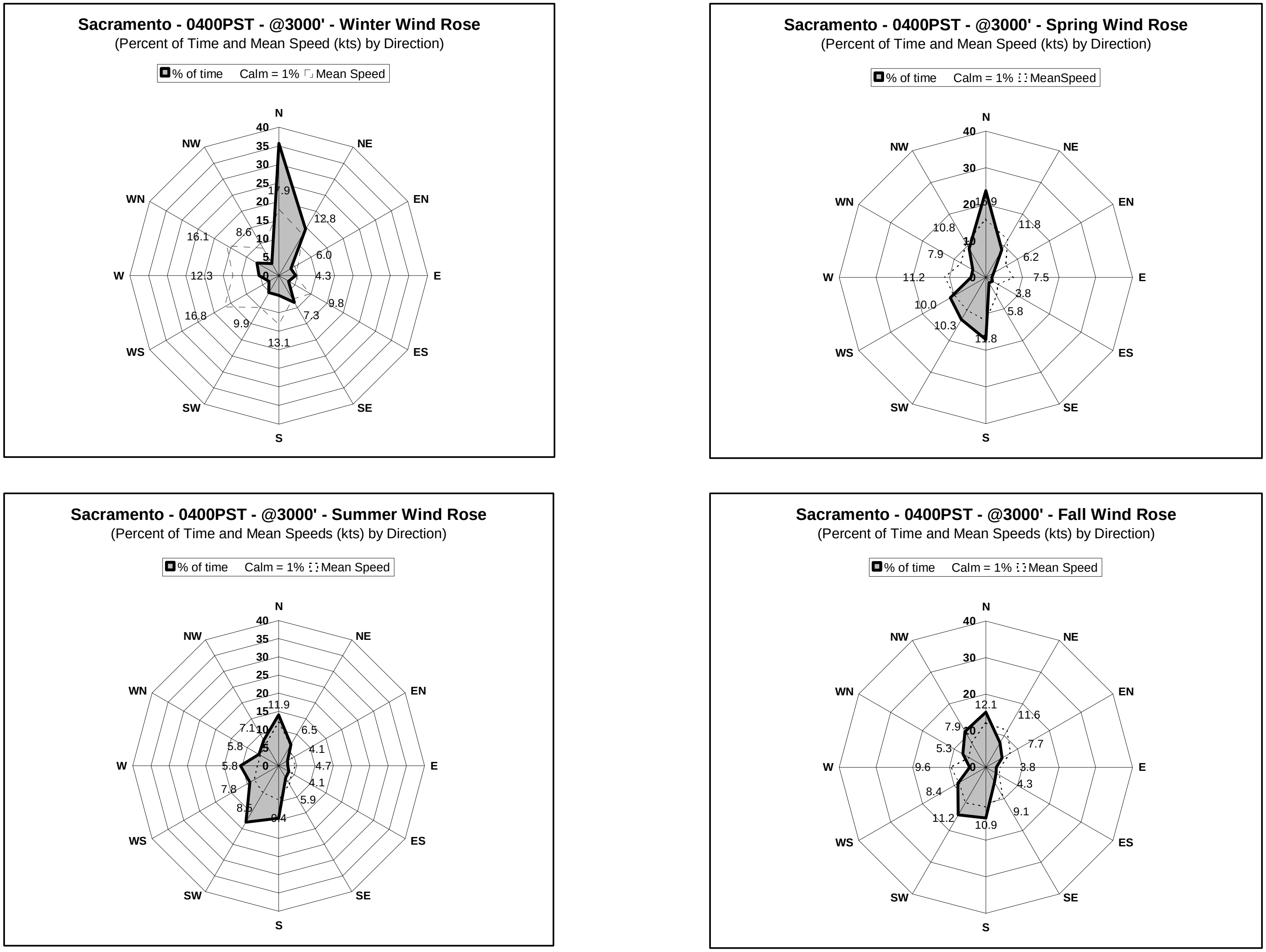


Figure 2-36b. Seasonal Summary of 1000 PST Winds at 3000 Feet AGL at Sacramento Executive Airport. (based on CARB, 1979)

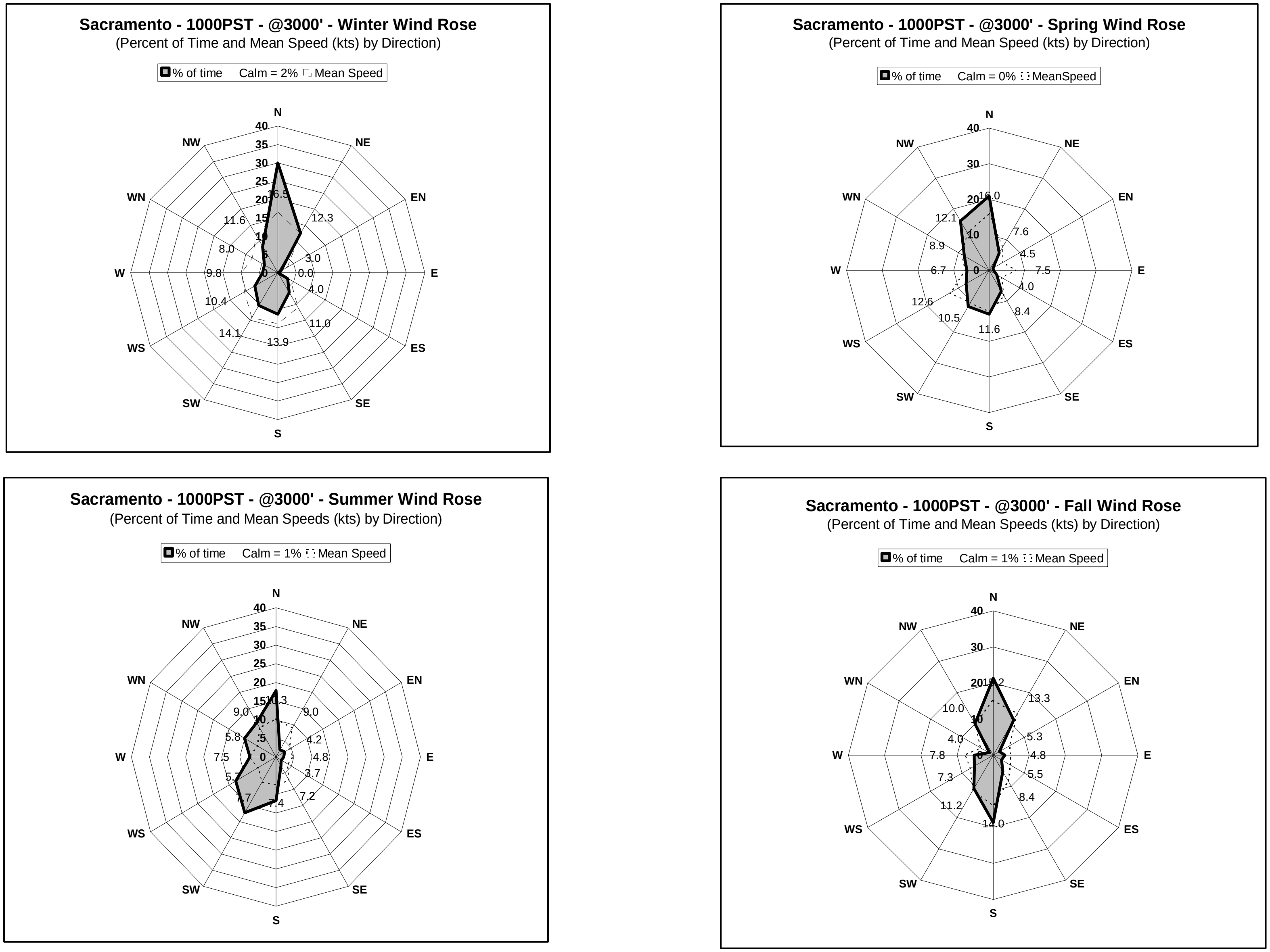


Figure 2-37c. Seasonal Summary of 1600 PST Winds at 3000 Feet AGL at Sacramento Executive Airport. (based on CARB, 1979)

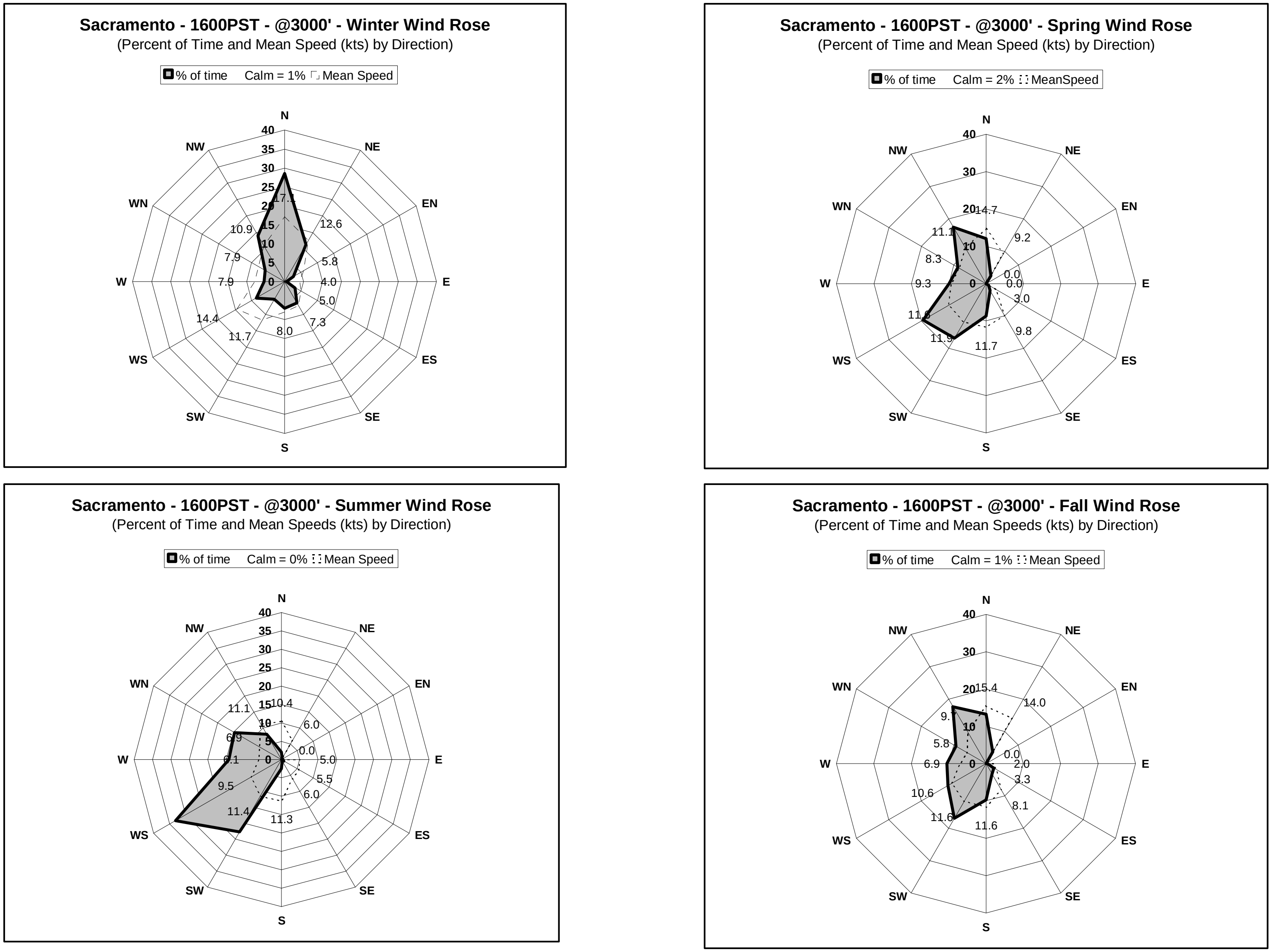


Figure 2-34. Altitude-Time Cross-Section of Wind Roses, SLT-Airport Radar Wind Profiler Lower Range Gates, Summer 2003.

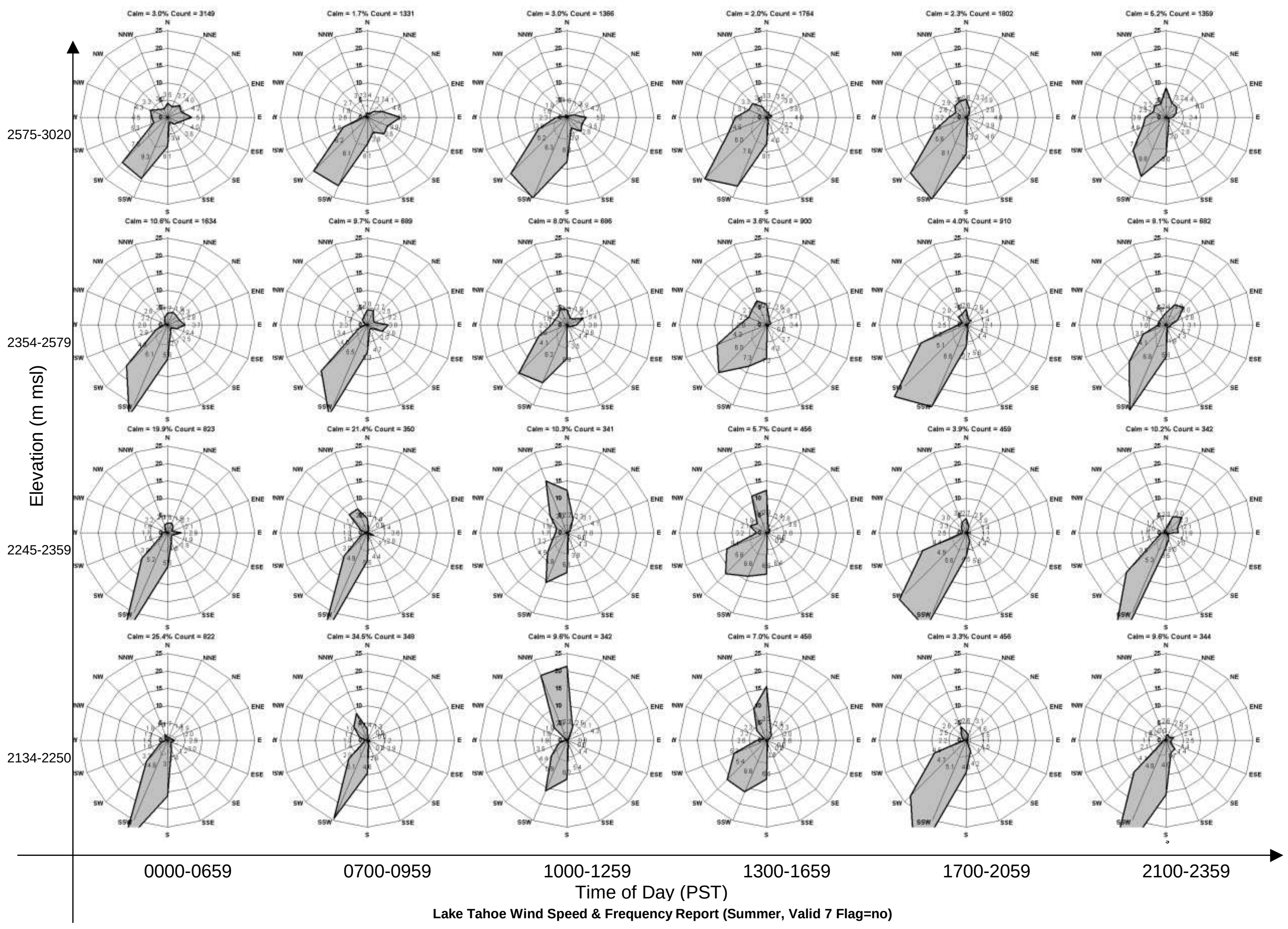
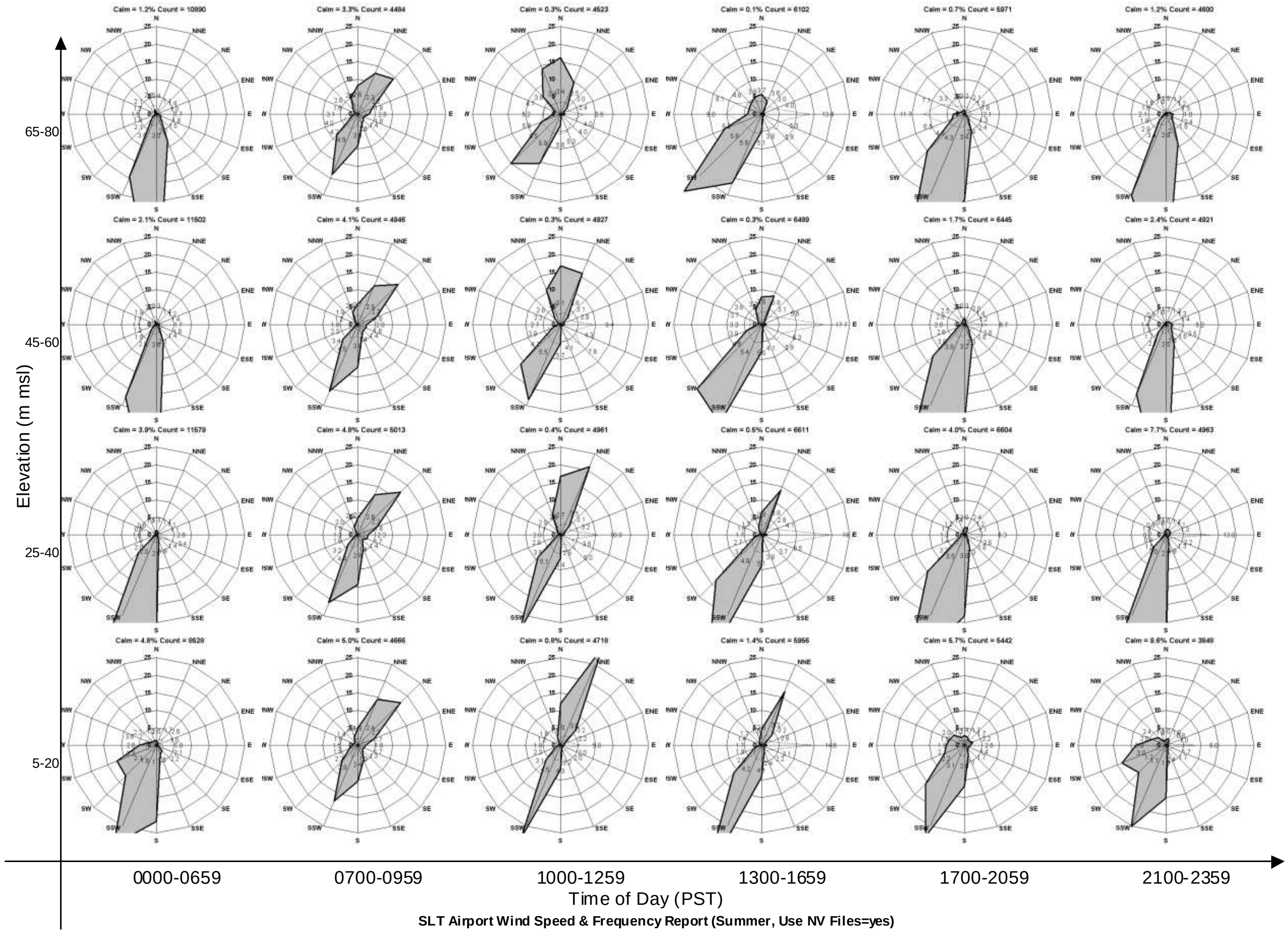


Figure 2-35. Altitude Time Cross-Section of Wind Roses for SLT-Airport Mini SODAR Lower Range Gates, Summer 2003.



2.4 Meteorological Impact on Air Quality

Emissions of natural and anthropogenic materials can vary diurnally, by day of week, seasonally, and annually. Depending on the meteorological conditions when they are emitted, the ultimate impact of the emissions can vary dramatically. Whether pollutants are of local or regional origin, once present over the Lake, the rates of deposition of the gases and particles will be strongly influenced by meso- and micro-scale meteorological conditions (e.g., turbulence, temperature gradients). These factors and the prediction of the hourly deposition rates are laid out in detail in Chapter 4.

Various scales of meteorological influences are at work in the Tahoe Basin and each can impact the air quality of the Basin. Global and synoptic scale meteorological processes can transport dust and gases from Asia to the Sierra Nevada in detectable amounts, especially during the spring (Appendix B; VanCuren, 2003). Synoptic scale meteorological processes can move air from the Pacific coast over the populated areas of the San Francisco Bay, Stockton, Sacramento, and the Sierra foothills into and over the Sierra Nevada. Ozone concentrations increase as air flows east from the San Francisco Bay Area, to the Central Valley, and to the foothills. Ozone concentrations decline over the Sierra Nevada and drop to just below the California health-based standard in the Tahoe Basin. Thus, the potential exists for impacts in the Tahoe Basin from global and synoptic scale movement of air contaminated by human and natural emissions (e.g., motor vehicles, smoke).

As is illustrated in **Figures 2-28 through 2-31**, the transition from down-slope to up-slope air flow in the Sierra Nevada tends to occur a few hours later during the winter than during the summer while the transition from up-slope to down-slope flow tends to occur a few hours later during summer than winter. The night-time down-slope flows tend to be stronger in winter than in other seasons while the up-slope flows during summer tend to be much stronger than during other seasons. Thus, the potential for transport of materials up the Sierra slopes toward Tahoe is greatest during the summer. Generously assuming westerly winds for 10 hours at 6 miles per hour during the summer yields a typical one-day transport distance of 60 miles. Typically, surface winds then generally will not result in direct transport from the Sacramento urban area to the Tahoe Basin in one day.

The potential for pollutants generated upwind to affect air quality in the Tahoe Basin requires both horizontal transport, which can be characterized by wind directions and speeds, and also vertical transport, whereby air that flows over the Sierra crest must mix down to lake level. Vertical mixing is limited by thermal stability of the atmosphere (i.e., temperature inversions, either aloft or surface-based). Over land areas, in the absence of storms or waves formed on the lee side of the Sierra, this mixing, as indicated by the vertical profiles of temperature and the comparisons of surface and aloft temperatures is generally limited to the daylight hours between a few hours after sunrise and a few hours before sunset. However, during winter and spring relatively warm Lake temperatures compared to air temperatures suggest that median mixing depths (for limited areas over the Lake) could potentially reach to between 500 and

1000 m above the Lake level. During summer and fall the median values of maximum mixing depth over the Lake are likely less than about 300 and 400 meters respectively.

What happens to contaminants originating from outside the Tahoe Basin when they arrive at Tahoe? Transported air parcels must pass over the Sierra Nevada (ridgeline at ~2500-3000 meters) and then descend to the lake surface at ~1900 meters. Thus, vertical downmixing of air must occur over at least 600 meters to reach the Lake's surface and 700-1000 meters if the transport is to be significant. Historical temperature soundings over Lake Tahoe (though relatively limited in number) consistently indicate a temperature inversion between about 3,000 and 3,300 feet MSL. Any air pollutants transported above that altitude would take special circumstances (e.g., deep convective mixing) to be transported through the inversion and to the lake.

Furthermore, surface-based inversions frequently occur at night and during winter. The presence of surface-based inversions due to radiative cooling, conductive cooling (e.g., shallow layer of air cooled from direct contact with cold water of Lake Tahoe), or advection (e.g., drainage of cooler air off the mountain slopes, movement onshore of the relatively cooler air over the lake surface) can have a very significant impact. Not only can they prevent material transported aloft from coming into contact with the lake, they also trap local emissions near the ground and, if advected over the Lake, near the Lake surface. However, the lake's warmth during these periods would tend to prevent surface inversions from occurring over the lake itself. Conversely, during summer days, the lake's coolness relative to the air temperature could cause shallow inversions over the lake. Thus, the complex meteorology associated with a large alpine bowl located in the eastern Pacific high pressure zone frequently creates temperature inversions (both near ground-level and above the crest of the Sierra) that inhibit the vertical exchange of pollutants.

The soundings of temperature and winds (rawinsondes and flights) available prior to LTADS suggested that nocturnal inversions are most common during the summer months, averaging 15 to 20 days per month. The depths of the surface-based inversions were generally between 150 and 350 feet. The LTADS observations confirm limited mixing over land sites due to nocturnal inversions in all seasons.

Additional LTADS observations of temperatures aloft provide an indication of the climatology of mixing depth. The temporal and spatial details of the vertical mixing are complex and thus limited measurements at a few locations cannot fully characterize the mixing. However, based on the available measurements and various assumptions previously discussed, the following characteristics of mixing are predicted. Over land persistent low level inversions dominate during hours of darkness during all seasons and deep mixing is generally limited to midday hours during summer and fall. Over the Lake, the maximum extent of vertical mixing over the Lake is probably similar during night and day and may be fairly deep during winter and spring. Generally however, maximum mixing depth over the Lake is probably about 300 meters or less during summer and 400 m or less during fall.

What happens to contaminants originating from within the Tahoe Basin? Emissions of natural and anthropogenic materials can vary diurnally, heptdominally (day of week), seasonally, and annually. Depending on the meteorological conditions when they are emitted, the ultimate impact of the emissions can vary dramatically. Based upon the dominant pattern of limited vertical mixing and downslope flows shortly before, during, and immediately following hours of darkness, local emissions occurring between late afternoon and mid morning the next day will have the greatest impact on the Lake. Deeper mixing over land and upslope/onshore flow between mid morning and late afternoon of fall and summer suggest that local emissions during those hours will have less impact on the Lake.

Emissions originating from outside the basin will have much less opportunity to interact with the Lake than local emissions do because the meso-scale wind patterns and inversions in and over the Tahoe Basin tend to keep local emissions near the ground and the transported emissions aloft or diluted. Mixing depths over the Lake will likely be greatest in winter and to a lesser extent in spring. Under these conditions of enhanced vertical mixing, concentrations are relatively dilute, but meteorological conditions alone do not necessarily preclude impacts from upwind sources. Although some emissions from upwind might be entrained into shallow downslope flows, the observations of diurnal variations in particle concentrations near the shoreline indicate otherwise. The downslope flows were relatively clean during early morning hours but particle counts were observed to increase quickly with the onset of local morning activity. An improved understanding of the spatial and temporal variations in both emissions and meteorological processes will greatly enhance our understanding of the spatial and temporal representativeness of measurements of ambient concentrations and atmospheric deposition to the Lake Tahoe.

Chapter 2 has described key meteorological factors that impact spatial and temporal patterns of pollutant concentrations in order to provide a foundation for interpreting the spatial and temporal variations in the observed concentrations reported in Chapter 3. Meteorological information is also used in predicting the rates of deposition of concentrations from the atmosphere to the Lake surface. These rates are determined in large part by the wind speed, surface roughness immediately upwind, and the rate of change of temperature with elevation immediately above the water surface. These relationships and the algorithms for prediction of the deposition rates are laid out in detail in Chapter 4. Additional summaries of meteorological data are also presented in Appendix D.

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